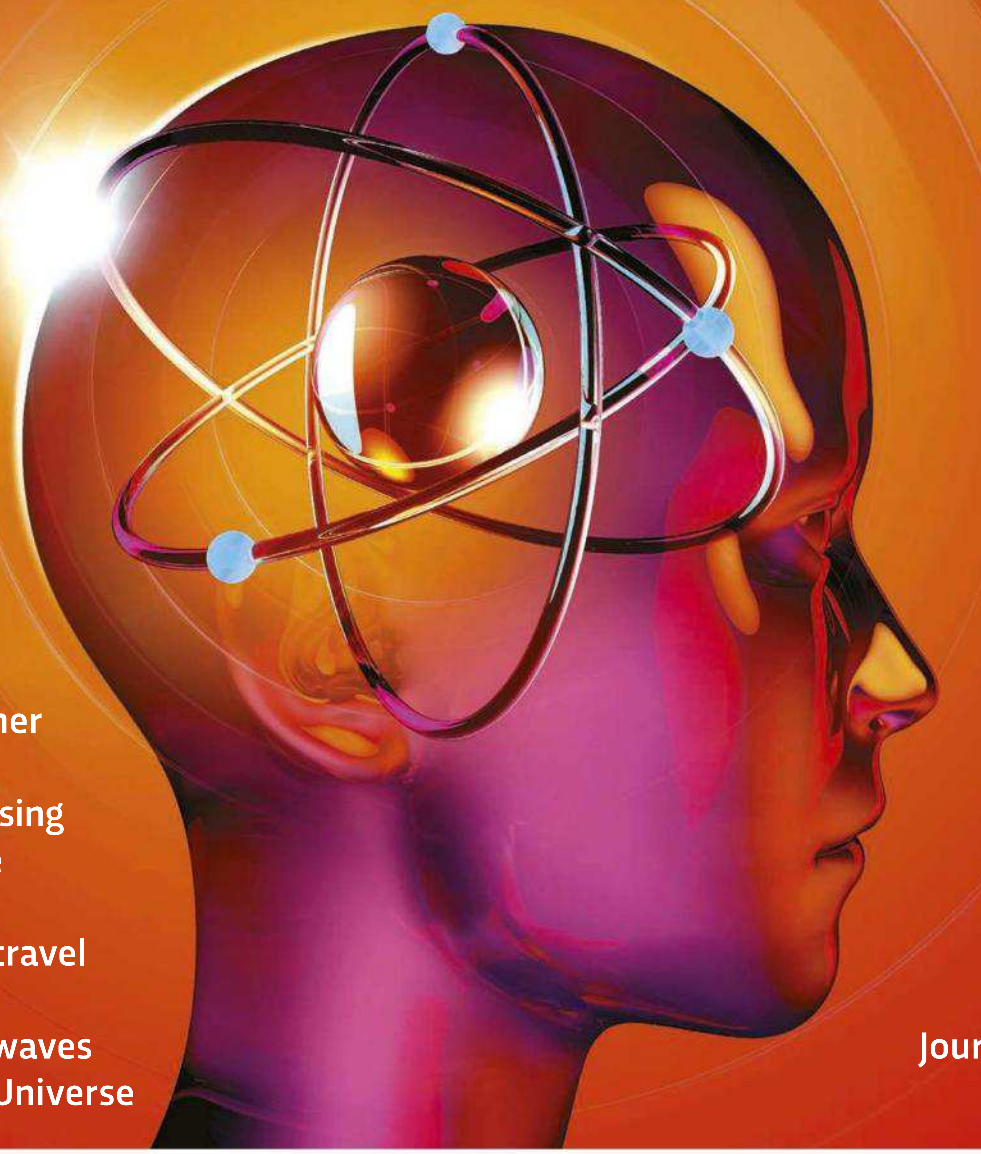
BBC

# FOCUS MAGAZINE Collection

VOL.06

# MIND-BENDING SCIENCE

## SIMPLY EXPLAINED



What Einstein got wrong

Stephen Hawking's final prediction

Inside the world's largest atom smasher

Hunting for the missing half of the Universe

The secret to time travel

How gravitational waves let us listen to the Universe

How the Universe will end

Quantum physics explained

Before the Big Bang

Brian Cox on space-time

Journey through a wormhole

COVER ILLUSTRATION: ANDY POTTS THIS PAGE: GETTY

# Brain-baffling ideas

Apparently, US physicist Richard Feynman used to say that "nobody understands quantum physics". Phew! There we all were thinking that if we couldn't get our heads round General Relativity, string theory or multiverses that we were destined to never win another pub quiz again. And Feynman even won a Nobel prize.

But, while hard physics topics like these can bend the mind, in this special issue of *BBC Focus*, we've enlisted the experts to explain in no-nonsense, down-to-earth, jargon-free lingo exactly how the Universe works, from the most minuscule of subatomic particles to the biggest of cosmological concepts. We're not saying it's easy to understand. Indeed, Danish physicist Niels Bohr (who won the 1922 Nobel prize in Physics) also reportedly said: "If anybody says he can think about quantum theory without getting giddy, it merely shows that he hasn't understood the first thing about it!"

Now, you might ask, why bother trying to set your head spinning understanding all this challenging science. Aside from impressing your mates, it's worth bearing in mind that there are all sorts of gadgets that we use every day that employ the concepts of modern physics. For example, we use torches, X-rays, mobile phones, we heat food in microwaves, we boil eggs on induction hobs... And that's just in the here and now. Reading this special issue will give you an idea of all the cool stuff that modern physics will someday enable – nanorobots, weird materials, flexi-screens, quantum computers, teleportation...

Enjoy the challenge!

**Daniel Bennett,** Editor

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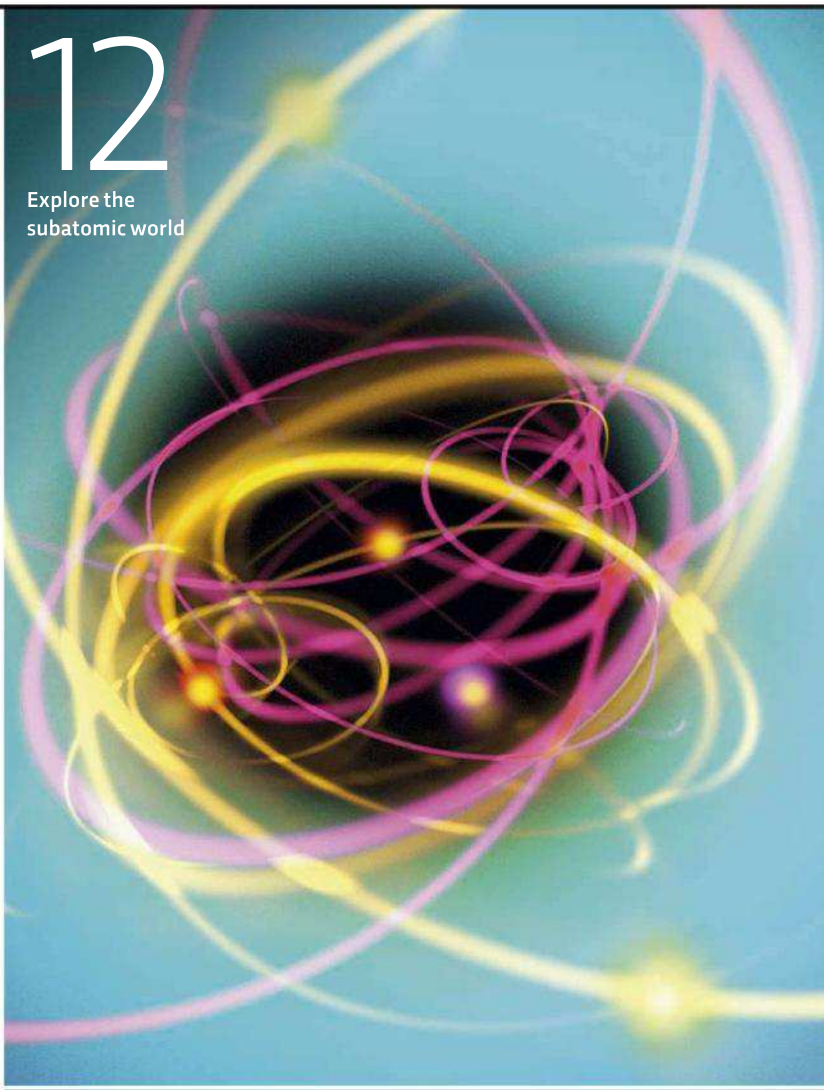


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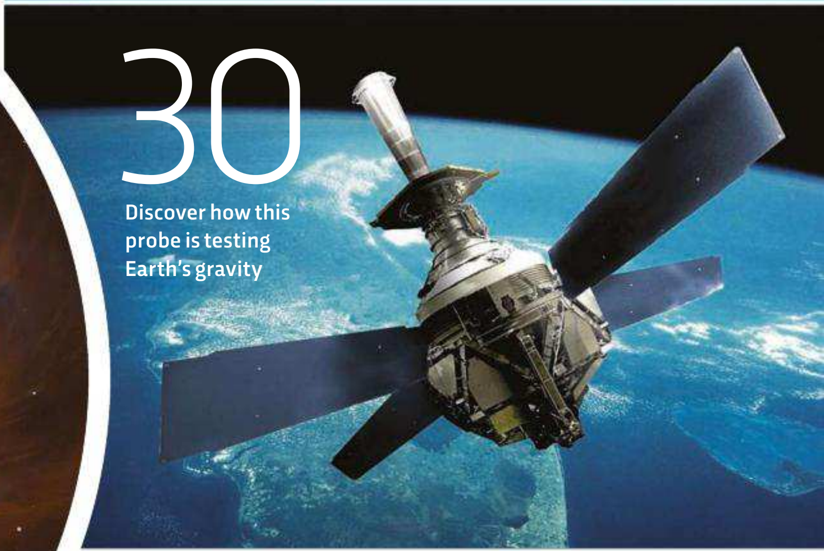


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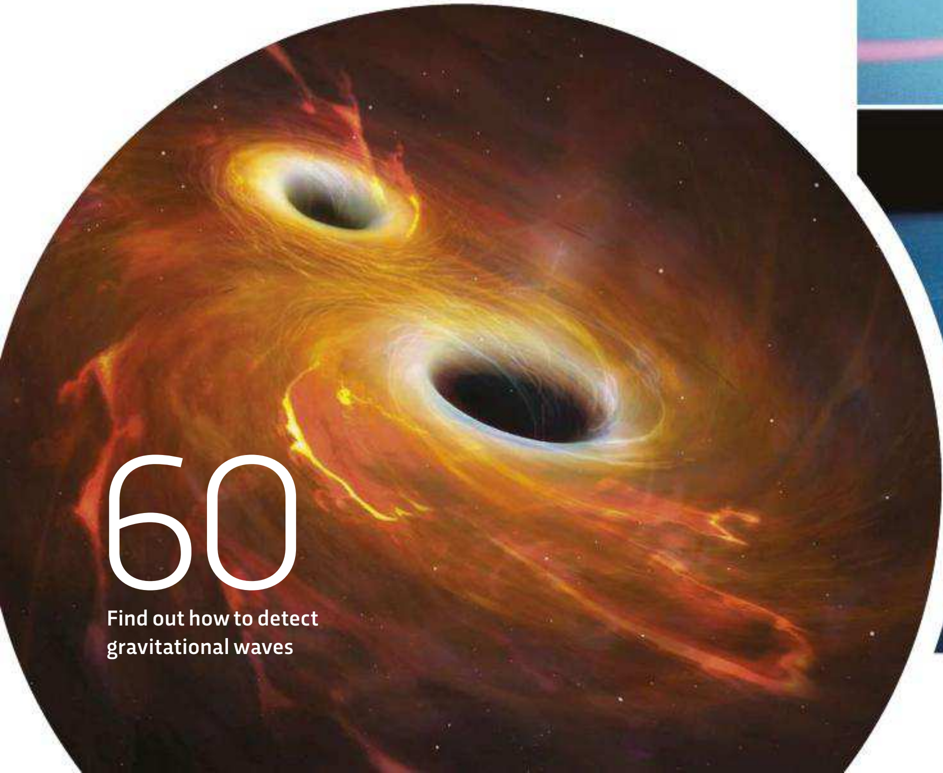


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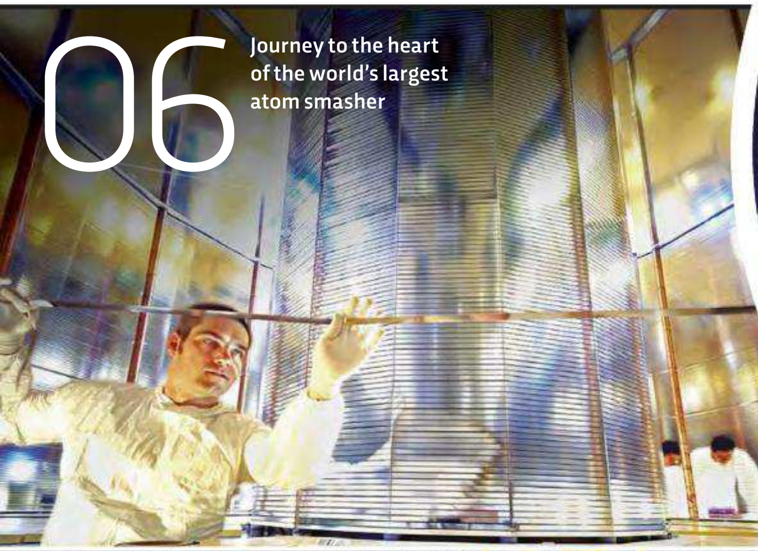
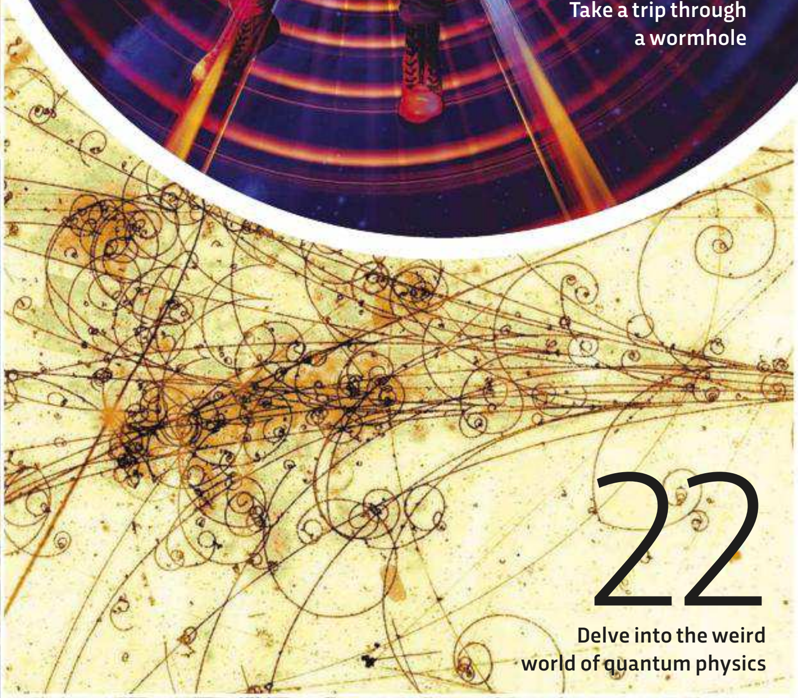
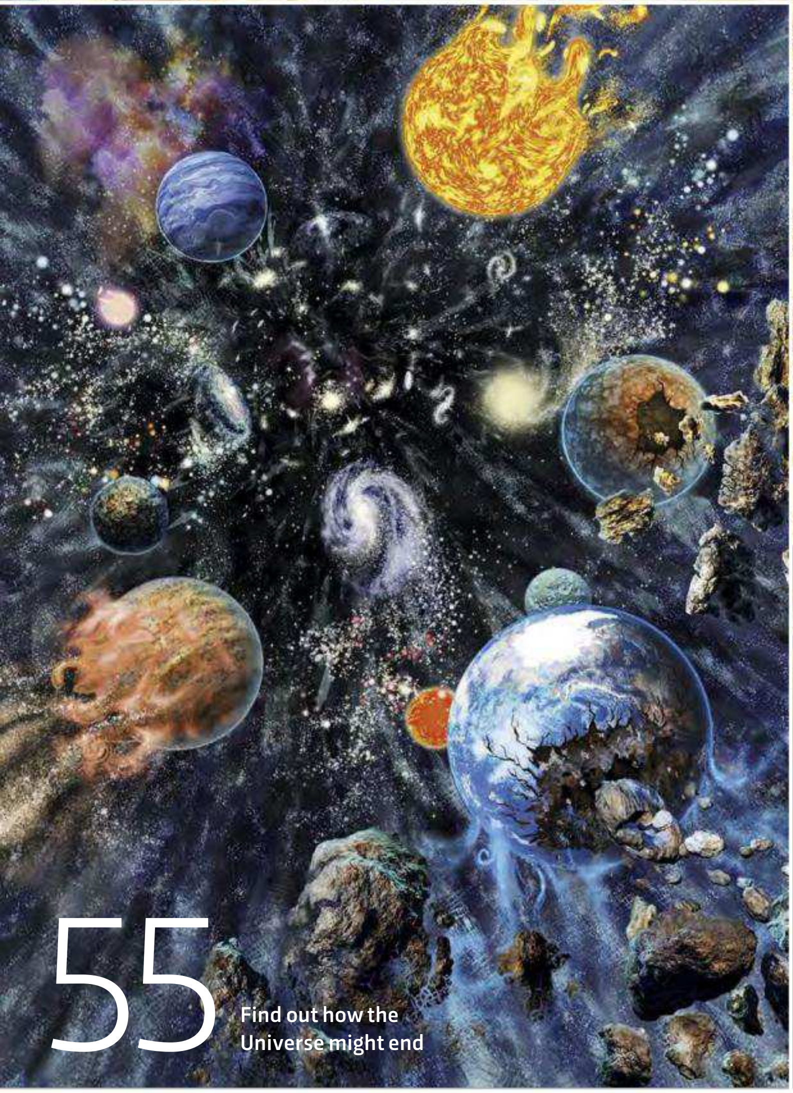















intel

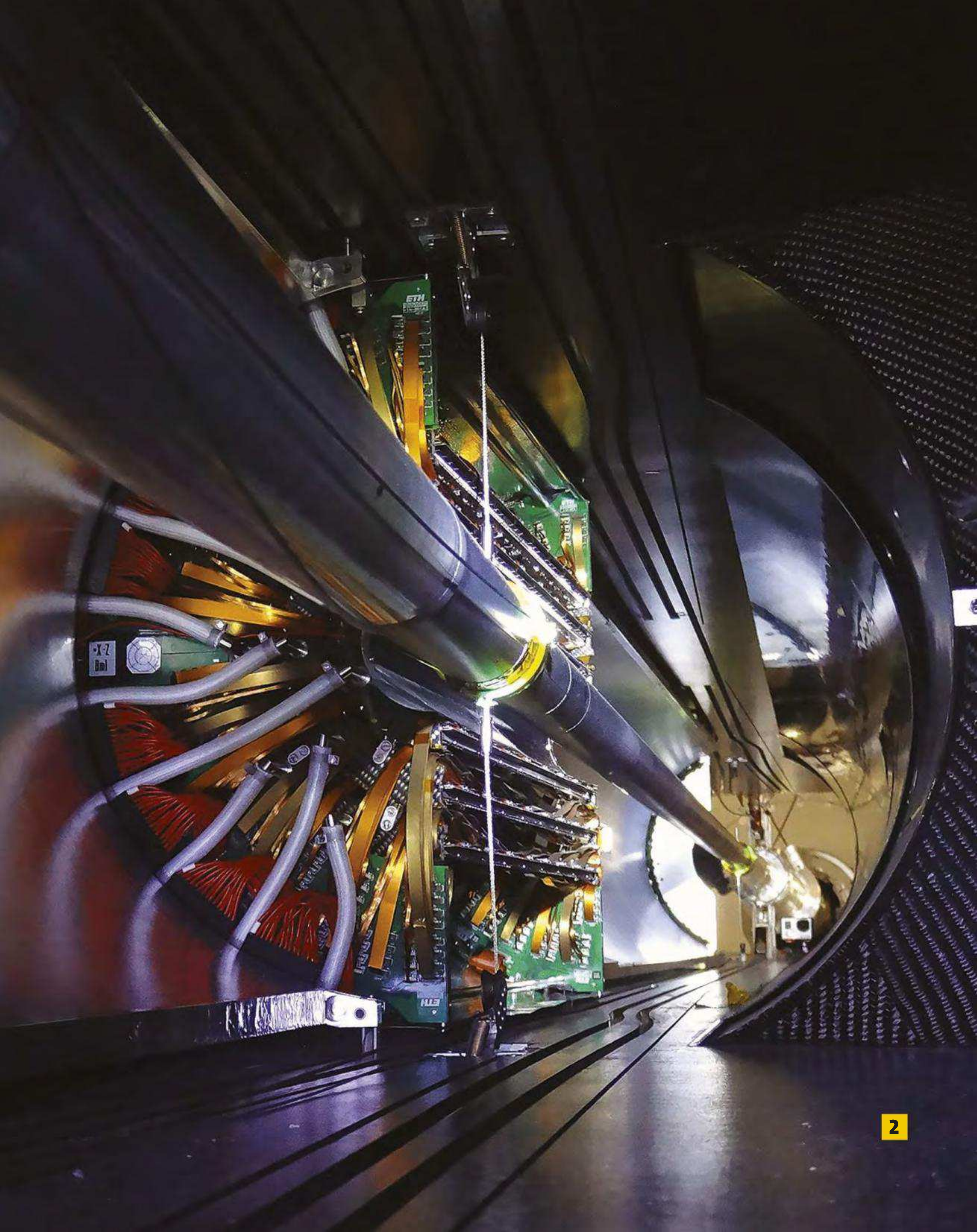
## 1. ATLAS

Nestled in a vast cavern, 100m below a Swiss village, the 7,000-tonne ATLAS detector is the largest ever constructed. It investigates all sorts of physical phenomena, from extra dimensions to dark matter. In July 2012, the teams at ATLAS and another LHC detector, CMS, both announced that they had observed a particle likely to be the elusive Higgs boson.


CERN

# ATOM SMASHER

The Large Hadron Collider (LHC) is the world's largest and most powerful particle accelerator. It sits in a 27km-circumference tunnel at CERN, 100m below the France-Switzerland border. Inside the tunnel, two beams of protons moving within a whisker of the speed of light collide head-on, recreating the conditions that existed around the time of the Big Bang. The beams are made to smash together at four different particle detectors around the ring: ATLAS, CMS, ALICE, LHCb.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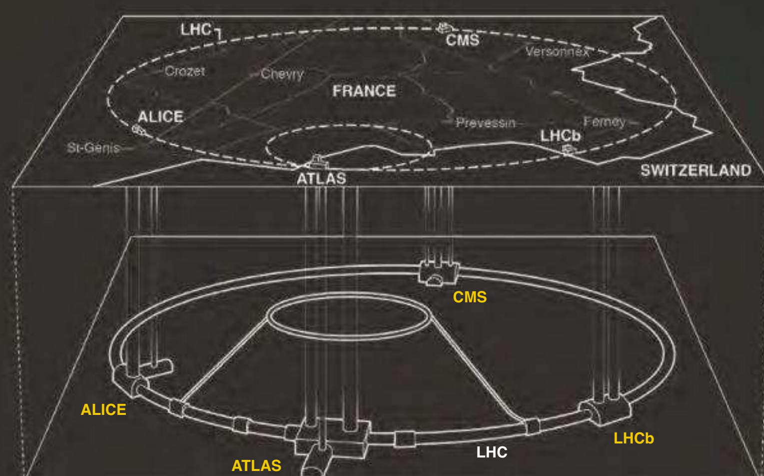
## 2. CMS

Like ATLAS, the CMS is a general purpose detector, researching a wide range of physics, but it uses a different magnet-system design. Alongside ATLAS, it detected the Higgs boson in 2012. The 14,000-tonne detector was constructed in 15 sections above ground and then assembled in a cavern below Cessy, France.

## 3. ALICE

ALICE is hunting for a weird state of matter that is believed to have formed just after the Big Bang. Particles smash together at temperatures 100,000 times hotter than the centre of the Sun. At these toasty temperatures, subatomic particles 'melt', releasing so-called 'quarks' from their bonds and creating the bizarre state of matter known as a 'quark-gluon plasma'.


## 4. LHCb

LHCb investigates the minuscule differences between matter and antimatter by studying a type of subatomic particle known as the 'beauty quark' or 'b quark'. The experiment differs from the others by using a series of detectors to spot particles that get hurled forward by the collision.

MICHAEL HOCH/CERN, GETTY, CDS/CERN

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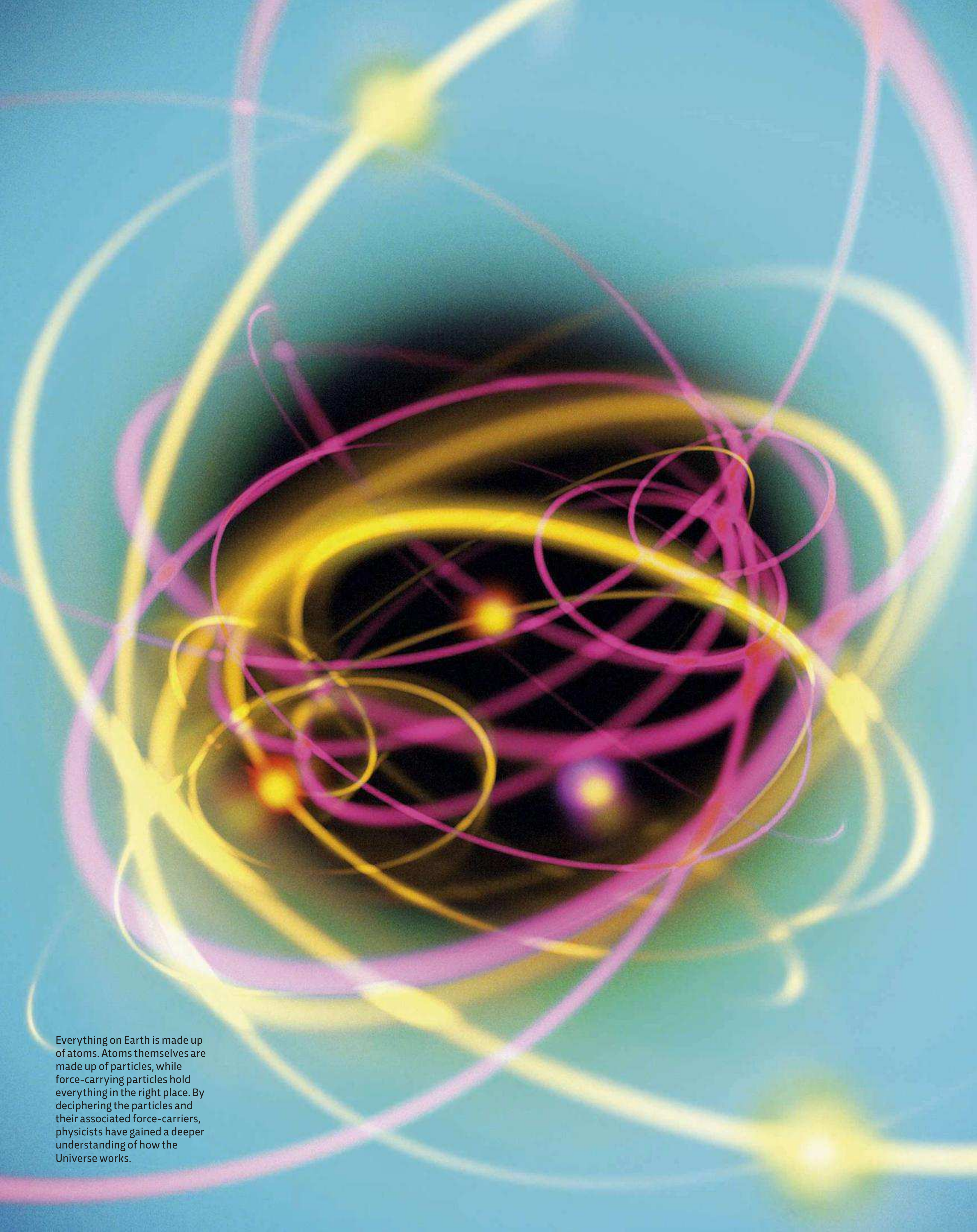
# PHYSICS

The Universe is built from elementary particles. This simple idea has existed since the time of the Ancient Greeks. Over the centuries we've come to understand the very fabric of stuff around us. In this section, we explore this weird quantum world and the nature of time.



Everything on Earth is made up of atoms. Atoms themselves are made up of particles, while force-carrying particles hold everything in the right place. By deciphering the particles and their associated force-carriers, physicists have gained a deeper understanding of how the Universe works.

# HOW DO WE KNOW WHAT MATTER IS MADE FROM?

Stars, skyscrapers, seaweed... everything is made from the same unimaginably tiny objects. Here, we delve into the strange world of particle physics

WORDS: **JON BUTTERWORTH**

Matter. Stuff. Everything we can see is made from atoms, each with electrons surrounding a tiny nucleus. And inside the nucleus are protons and neutrons, each made of quarks. Add a horde of neutrinos flying around us, elusive and insubstantial, and that's where it stops. So says the Standard Model of particle physics, the best theory we currently have for explaining what all the visible matter in our Universe is made from.

But how do we know this? Much of our knowledge comes from scattering experiments – that is, bouncing one thing off another. We have discovered new elements, and new fundamental particles, by carrying out scattering experiments at high-energy particle accelerators around the world. But scattering isn't the only way to find out what the Universe is made of... our story begins in a Manchester lab at the beginning of the 19th Century.

John Dalton is widely considered as the father of atomic theory. As a chemist, physicist and meteorologist working in Manchester, he measured the weights of materials involved in various chemical reactions, and showed that different elements always combined in fixed ratios. This was consistent with the idea that there existed a smallest unit of any chemical element – the atom – that makes up everything we see around us.

More elements, and hence types of atom, were discovered over the following years and, in 1869, Russian chemist Dmitri Mendeleev made a major breakthrough by arranging

GETTY

> **It was like firing a 15-inch shell at a piece of tissue paper and it coming back to hit you. This could only be explained if the atom's mass is densely concentrated**

them into the periodic table, according to their chemical and atomic properties.

While the order and predictability of the chemical elements was good evidence for the existence of atoms, scientists wondered if there could be even smaller particles. In 1897, physicist JJ Thomson was studying 'cathode rays' at Cambridge University. Cathode rays are emitted by a hot metal and are accelerated by electric and magnetic fields. Thomson discovered that the cathode rays were made up of tiny particles, much lighter than an atom and of the same charge and mass, no matter what metal was used in his experiment. These were electrons, the first subatomic particles to be discovered.

It was thought that these particles were present inside the atom. But as the electrons appeared

Nuclear physicists, Rutherford and Geiger with their apparatus for counting alpha particles

GETTY, ALAMY

# PERIODIC TABLE OF ELEMENTS

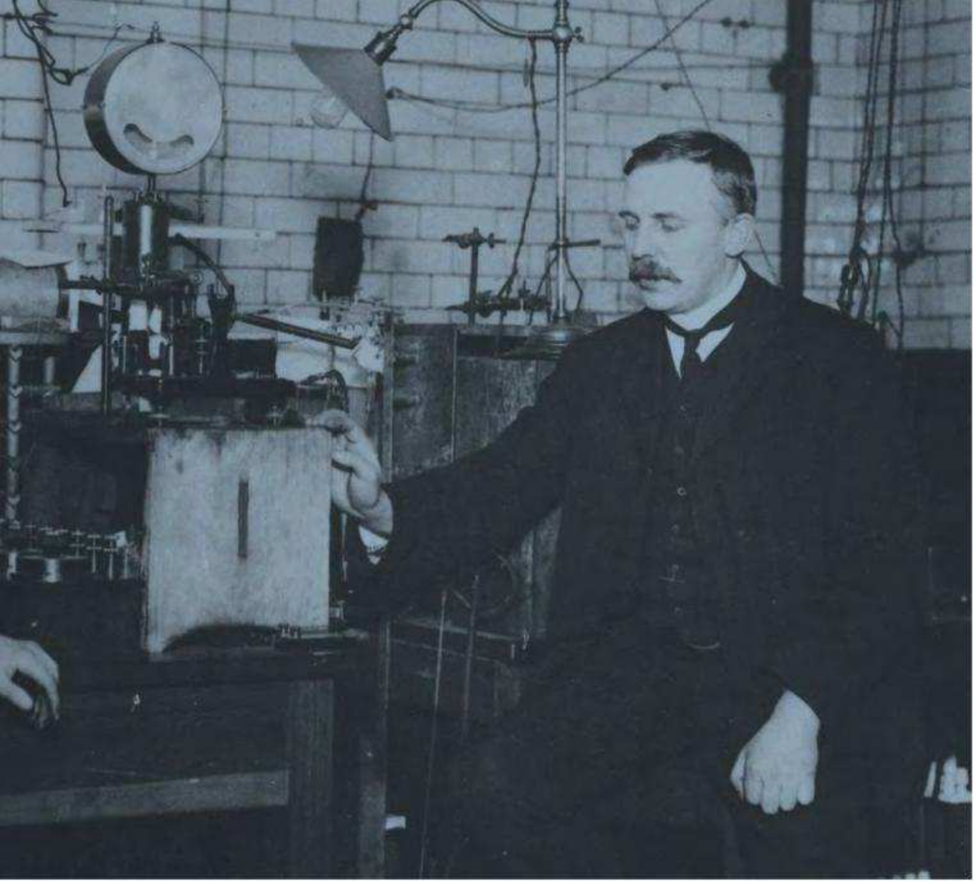
All the elements in the periodic table are made up of protons, electrons and neutrons. But what makes them all different is the number of protons in the nucleus. For example, hydrogen only has one proton, while uranium has 92.

In 1869, Dmitri Mendeleev created the periodic table by putting all the elements in order of increasing numbers of protons and put elements with similar properties in the same column.

- Alkali Metal
- Alkaline Earth Metal
- Transition Metal
- Post-Transition Metal
- Metalloid
- Polyatomic Nonmetal
- Diatomic Nonmetal
- Noble Gas
- Lanthanide
- Actinide
- Unknown Properties

1 — ATOMIC NUMBER (No. of protons)
1.008 — ATOMIC WEIGHT
H — SYMBOL
Hydrogen — ELEMENT NAME

| | | | |
|---|---|---|---|
| 1 | H | Hydrogen | 1.008 |
| 3 | Li | Lithium | 6.94 |
| 4 | Be | Beryllium | 9.0122 |
| 11 | Na | Sodium | 22.990 |
| 12 | Mg | Magnesium | 24.305 |
| 19 | K | Potassium | 39.098 |
| 20 | Ca | Calcium | 40.078 |
| 21 | Sc | Scandium | 44.956 |
| 22 | Ti | Titanium | 47.867 |
| 23 | V | Vanadium | 50.942 |
| 24 | Cr | Chromium | 51.996 |
| 25 | Mn | Manganese | 54.938 |
| 26 | Fe | Iron | 55.845 |
| 27 | Co | Cobalt | 58.933 |
| 28 | Ni | Nickel | 58.693 |
| 37 | Rb | Rubidium | 85.468 |
| 38 | Sr | Strontium | 87.62 |
| 39 | Y | Yttrium | 88.906 |
| 40 | Zr | Zirconium | 91.224 |
| 41 | Nb | Niobium | 92.906 |
| 42 | Mo | Molybdenum | 95.95 |
| 43 | Tc | Technetium | (98) |
| 44 | Ru | Ruthenium | 101.07 |
| 45 | Rh | Rhodium | 102.91 |
| 46 | Pd | Palladium | 106.42 |
| 55 | Cs | Caesium | 132.91 |
| 56 | Ba | Barium | 137.33 |
| 57 | La | Lanthanum | 138.905 |
| 72 | Hf | Hafnium | 178.49 |
| 73 | Ta | Tantalum | 180.95 |
| 74 | W | Tungsten | 183.84 |
| 75 | Re | Rhenium | 186.21 |
| 76 | Os | Osmium | 190.23 |
| 77 | Ir | Iridium | 192.22 |
| 78 | Pt | Platinum | 195.08 |
| 87 | Fr | Francium | (223) |
| 88 | Ra | Radium | (226) |
| 89 | Ac | Actinium | (227) |
| 104 | Rf | Rutherfordium | (267) |
| 105 | Db | Dubnium | (268) |
| 106 | Sg | Seaborgium | (271) |
| 107 | Bh | Bohrium | (272) |
| 108 | Hs | Hassium | (277) |
| 109 | Mt | Meitnerium | (281) |
| 110 | Ds | Darmstadtium | (281) |
| 58 | Ce | Cerium | 140.12 |
| 59 | Pr | Praseodymium | 140.12 |
| 60 | Nd | Neodymium | 144.24 |
| 61 | Pm | Promethium | (145) |
| 62 | Sm | Samarium | 150.36 |
| 63 | Eu | Europium | 151.96 |
| 64 | Gd | Gadolinium | 157.25 |
| 65 | Tb | Terbium | 158.93 |
| 90 | Th | Thorium | 232.04 |
| 91 | Pa | Protactinium | 231.04 |
| 92 | U | Uranium | 238.03 |
| 93 | Np | Neptunium | (237) |
| 94 | Pu | Plutonium | (244) |
| 95 | Am | Americium | (243) |
| 96 | Cm | Curium | (247) |
| 97 | Bk | Berkelium | (247) |

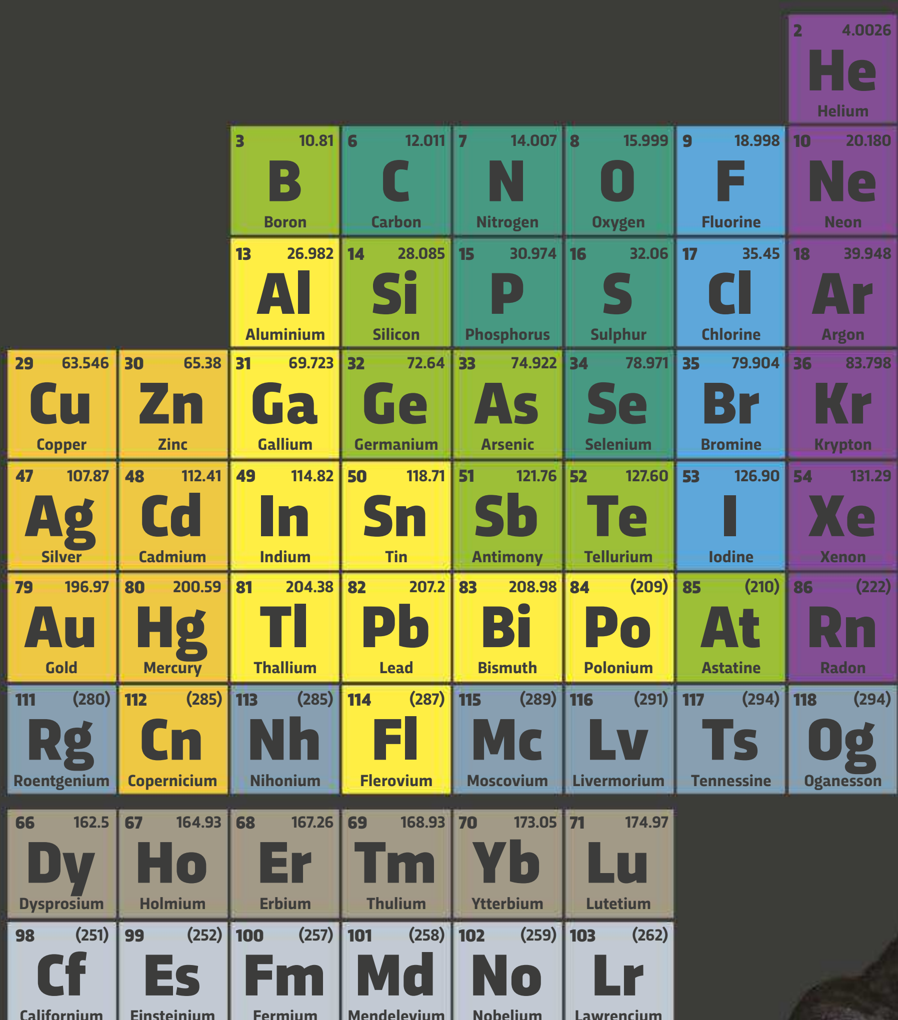


to be so light, it was assumed that there must be other stuff within the atom to account for most of its mass. It was not known what this other stuff might be, or how the electrons might be distributed among it.

One idea, proposed by Thomson, was that the electrons were distributed throughout the atom like raisins through a plum pudding. Surprisingly, plum puddings don't have any plums in them, but this is nothing compared to the surprise received by Hans Geiger and Ernest Marsden – two physicists working in Manchester under the direction of Ernest Rutherford. To try and understand subatomic structure, they fired a beam of alpha particles (see Jargon Buster on page 16) at gold foil. They were expecting the particles to pass straight through, but some of them bounced back. It was a result that Rutherford famously described as like firing a 15-inch shell at a piece of tissue paper and it coming back to hit you. This could only be explained if the overwhelming majority of the atom's mass was concentrated in a volume thousands of times smaller than the atom itself. This is indeed the case – this dense concentration is the atomic nucleus.

The lightest atomic nucleus belongs to hydrogen. Its nucleus consists of a single proton, which can be exposed by removing the single electron from the atom. Scientists measured the mass and charge of various nuclei, and came up with a problem: if the nucleus purely consisted of protons, then this would leave the atom having too much positive electric charge.

James Chadwick – another physicist working for Rutherford – was one of those convinced that there must be another kind of particle in the atom, with a mass about the same as the proton but with zero electric charge. In 1932 he discovered it. This was no easy task, since most of the methods for detecting particles relied upon the fact that they knock electrons off other atoms. This leaves a




In 1869, Russian chemist Dmitri Mendeleev created the periodic table

## JARGON BUSTER

**ALPHA PARTICLE**
These are helium nuclei – two protons and two neutrons bound together. They are produced in many radioactive decays.

**BETA DECAY**
The decay of an atomic nucleus, which involves the transition of a neutron into a proton.

**BOSON**
The forces of the Standard Model are all carried by particles called bosons.

**GLUON**
These are a type of boson that carry the strong force. They 'glue' quarks together.

**HADRON**
A particle made of quarks and/or antiquarks.

**LEPTON**
A particle that does not feel the strong force. Electrons and neutrinos are leptons.

**PHOTON**
The carrier of the electromagnetic force.

**QUARK**
A particle that is bound inside hadrons by the strong force.

**HIGGS BOSON**
This particle gives mass to the elementary particles.

**ELECTROMAGNETIC FORCE**
This force is responsible for electricity and magnetism. It governs how fridge magnets work, how atoms stick together and how light interacts with matter.

**STRONG FORCE**
This force binds the atomic nucleus together, and confines quarks inside hadrons.

**WEAK FORCE**
The short-range force responsible for beta decay.

**SYMMETRY**
This is the idea that something looks the same before and after a particular transformation. For example, a square looks the same before and after it is rotated through an angle of 90°.

**GAUGE SYMMETRY**
This specific symmetry governs the equations that describe how the elementary particles interact with each other.

**STANDARD MODEL**
This brings together all known elementary particles. It is a unified theory describing the electromagnetic, weak and strong forces, but it does not include gravity or dark matter.

charged particle (ion) that can be easily detected using a device called a cloud chamber. As neutrons have no charge, they cannot be detected in a cloud chamber.

Chadwick got around the problem by exploiting the fact that neutrons have almost the same mass as a proton, which means that they'll effectively transfer their energy, in much the same way as a fast-moving cue ball transfers its energy to a stationary snooker ball. So Chadwick fired neutrons – produced when beryllium was bombarded by alpha particles – into various materials containing protons, and detected the protons when they emerged from the other side. This told him that the mysterious beam coming from the beryllium indeed consisted of neutral particles of similar mass to the proton – the sought-after neutron. At this point, the basic constituents of matter seemed to be known. With protons, neutrons and electrons you could build every element in the periodic table, and with those elements you could build anything. But the way the particles interacted was not understood. For example, how could a bunch of protons, which were all positively charged and therefore ought to be repelled from each other, manage to stay crammed together in the nucleus? Also, during their studies, scientists had come across a type of radioactive decay called 'beta decay' (see Jargon Buster, left). Beta decay was problematic as it seemed to violate the law of momentum conservation, which is one of the fundamental principles of physics. There must have been something else at work...

### GOING DEEPER

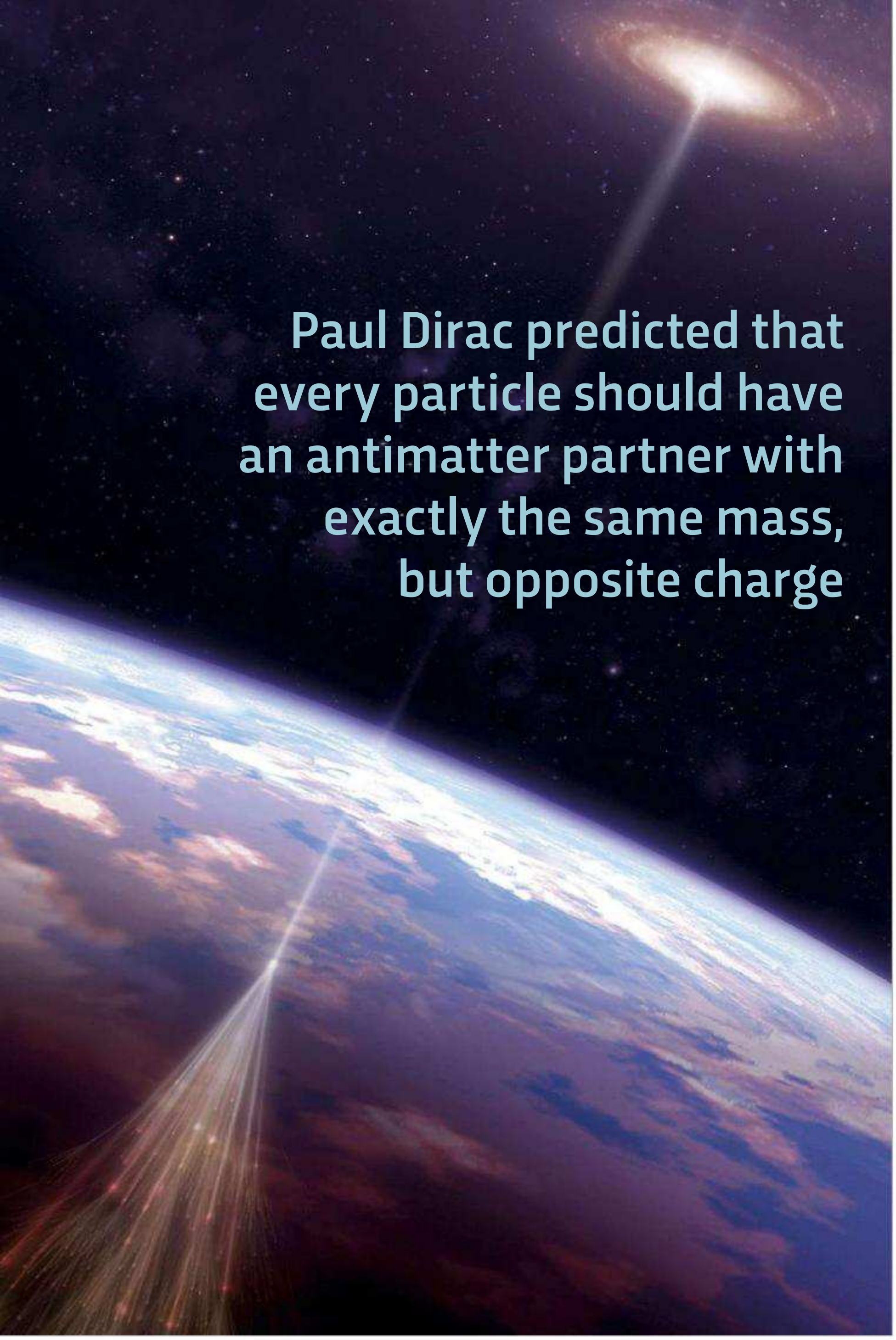
Back in 1909, physicist Theodor Wulf had shown that there were more charged particles than he expected at the top of the Eiffel Tower. This was ascribed to high-energy particles bombarding us from space – so-called cosmic rays. Scientists started using particle detectors at the tops of mountains, in hot air balloons or in aeroplanes to study these rays. Intriguing new particles began showing up which were not protons, neutrons or electrons, nor any combination of them. They called these particles 'hadrons' from the Greek meaning 'bulky' or 'thick', as they were generally much more massive than



Artist's impression of cosmic rays hitting the Earth's atmosphere, creating a shower of subatomic particles

## TIMELINE

*Our quest to understand matter has stretched some of science's greatest minds*



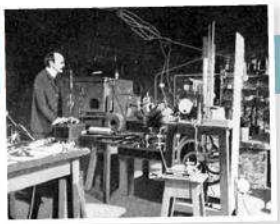
**Paul Dirac predicted that every particle should have an antimatter partner with exactly the same mass, but opposite charge**

electrons. The lightest of the hadrons, the pion, was discovered in 1947. Many followed – a Greek alphabet soup of lambdas, rhos, sigmas and omegas. The large number of them was a worrying problem for anyone hoping for an elegant theory of fundamental physics.

Meanwhile, the beta decay problem was 'solved' by inventing a new, tiny, neutral particle – the neutrino. In 1930, theoretical physicist Wolfgang Pauli said, rather shamefacedly, "I have done a terrible thing, I have postulated a particle that cannot be detected." He was right about the neutrino, but wrong about the impossibility of detection.

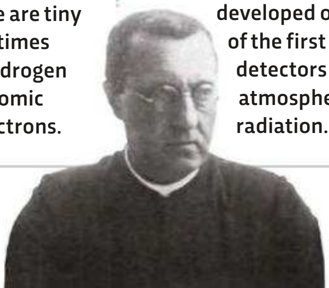
He wasn't the only one postulating new particles. In 1928, physicist Paul Dirac published his famous equation which unified quantum mechanics with Einstein's Special Relativity, and predicted that every particle should have an antimatter partner with exactly the same mass, but opposite charge. The positron – the antimatter counterpart of the electron – was discovered in cosmic ray observations four years later in 1932.

Back with the neutrino. In 1953, Frederick Reines and Clyde Cowan in South Carolina carried out an experiment that proved the neutrino was not just a figment of Pauli's imagination. They observed reactions caused by antineutrinos scattering off protons and producing positrons and neutrons. The chances of a neutrino, or antineutrino, actually interacting are very small. Despite the fact they placed their detector in an intense beam of neutrinos produced from the billions of



**1897**
JJ Thomson shows that the 'rays' emitted in a cathode ray tube are tiny particles, 2,000 times lighter than a hydrogen atom. The subatomic particles are electrons.

**1909**
Physicist Theodor Wulf discovers more charged particles at the top of the Eiffel Tower than the bottom, due to 'cosmic rays' from space. He developed one of the first detectors for atmospheric radiation.



**1910**
New Zealand-born physicist Ernest Rutherford investigates the scattering of alpha rays and the inner structure of the atom which caused the scattering, leading to his idea of a 'nucleus' – his greatest contribution to science.

**1928**
Paul Dirac devises an equation capable of describing electrons moving at 'relativistic' speeds – close to the speed of light. The equation predicts the existence of antimatter.

**1956**
Chinese-American physicist Chien-Shiung Wu observes that the weak force has 'handedness' – it cares about the difference between left and right. This impacts the structure of the Standard Model.

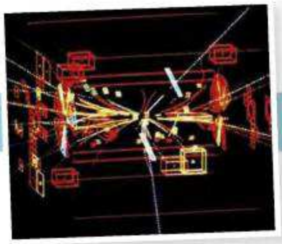
The Higgs boson was discovered at the Large Hadron Collider, pictured here with Peter Higgs himself

interactions inside a nuclear reactor, they saw few events – but enough to be conclusive.

The detection of neutrinos was great progress, but the problem of 'too many hadrons' just got worse. But then, even tinier particles that make up the hadrons were postulated: quarks. Six different types of quark were revealed, starting in 1967 and ending with the discovery of the heaviest quark in 1995. Quarks and electrons were enough to explain the matter content of atoms, and thus all elements.

But in parallel, physicists were developing an understanding of the forces responsible for holding atoms together. In the 1940s, Richard Feynman, Julian Schwinger and Sin-Itiro Tomonaga had developed 'quantum electrodynamics', a quantum theory of electromagnetism. Over a number of years in the 1970s, electromagnetism's equivalent for the strong force (which confines quarks inside hadrons) was also put together. This was known as 'quantum chromodynamics'. However, a third force, the weak force (responsible for beta decay) presented some problems.

Quantum electrodynamics and quantum chromodynamics both work because they are based on the symmetries of nature – aspects of physics that can be changed without altering the forces or the particles, in the same way that a square can be rotated by 90° and still look the same. Without these symmetries, the

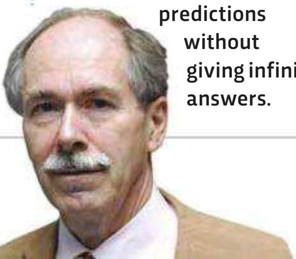


## 1973
**The electrically neutral component of the weak force is discovered at CERN's Gargamelle experiment. This brings together the electromagnetic and strong forces.**

## 1979
**US physicist Steven Weinberg wins a Nobel prize for combining electromagnetism and the weak force, and hence helping to evolve the Standard Model.**

## 1998
**Neutrinos, long thought to be massless, are discovered to have mass by scientists working at the Super-Kamiokande neutrino observatory in Japan. This changes the Standard Model.**

## 1999
**Dutch physicist Gerardus 't Hooft wins a Nobel prize for making a crucial contribution to the Standard Model by proving that the theory is able to make precise predictions without giving infinite answers.**



## 2012
**The Higgs boson is finally discovered at CERN, proving the existence of the 'Higgs field' that gives fundamental particles their mass.**

CERN X2, GETTY X2, CLAUDIA MARCELLONI

**Does the pattern of the Standard Model particles contain a clue to another layer of substructure, of even smaller things, that the quarks and leptons are made of?**

theories give nonsense answers. In the Standard Model, all the forces are carried by particles called bosons. But if you plug the symmetries into the equations of the Standard Model, it turns out that the particles which carry the forces have to be massless. This is fine for the carriers of the strong force (the gluon) and the electromagnetic force (the photon), but not for the weak force, which is carried by heavy, massive particles known as the W and Z bosons.

The solution exists in a theory developed in 1964 by Robert Brout, François Englert, Peter Higgs and others. They postulated a new energy field present everywhere in the Universe, and particles acquire mass by interacting with this field. In this way, the vital symmetry of the theory could be preserved, but the W, Z and other particles could have their observed mass. The theory also predicted a new, massive particle with zero charge. The Higgs boson, the missing piece of the Standard Model, was discovered at CERN's Large Hadron Collider in 2012 (see page 6).

But could there be another twist? According to their properties, the matter particles of the Standard Model are arranged in a pattern. There are six flavours of quark and six of leptons (see Jargon Buster on page 16), and they all come in three 'generations' of increasing mass. This is intriguing. Mendeleev gave us a huge clue to the substructure of atoms when he arranged the elements in the periodic table. The pattern of hadron properties was what led scientists to postulate the existence of quarks. Does the pattern of the Standard Model particles contain a clue to another layer of substructure, of even smaller things, that the quarks and leptons are themselves made of? We don't know. But with more experiments we are trying to find out.

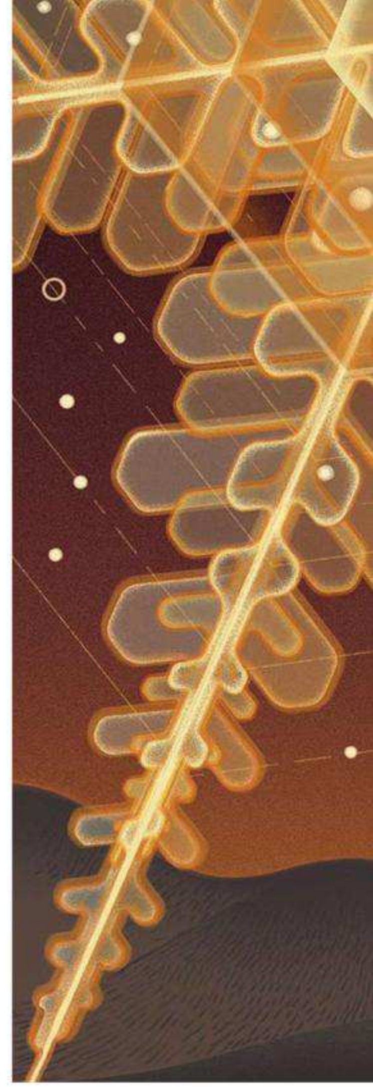
## STANDARD MODEL OF ELEMENTARY PARTICLES


These are the elementary particles, which together make up the Standard Model of particle physics. All of the atoms in the Universe are built using only the electrons and the 'up' and 'down' quarks. These interact with each other and stick together with the help of gluons and photons. Gluons transmit what is known as the 'strong force' that binds together quarks to make protons and neutrons, the building blocks of atomic nuclei. Photons transmit the electromagnetic force that acts between electrically charged particles, like electrons. The other particles in the table are also important, but for less evident reasons. For example, around 60 billion electron neutrinos stream through every square centimetre of your body every second. These neutrinos are made inside the Sun, as a by-product of the process that fuses hydrogen into helium. The 'weak force' is responsible for this process of nuclear fusion and is transmitted by the W and Z particles.

The particles in the second and third columns of the Standard Model are like heavier copies of those in the first column. The existence of these heavier particles was crucial in governing the behaviour of the Universe shortly after the Big Bang.

**Prof Jon Butterworth** is a physics professor at UCL, who works on the ATLAS experiment at the Large Hadron Collider.

Jeff Forshaw and Brian Cox
**EXPLAIN THE UNIVERSE**



# THE RULES OF THE GAME

**The laws that govern particle physics help us understand how the Universe behaves**

WORDS: **JEFF FORSHAW AND BRIAN COX**

Like them or not, rules govern our lives. Some we make, and some we break. But zoom out, and there's one set of rules that overrides them all. These are the rules of particle physics, and if we get to grips with them, we can understand what everything in the Universe is made from, and why everything behaves as it does.

The basic rules are not complicated: each particle can hop around, and in doing so can emit or absorb other particles. For example, an electron can hop from one place to another, emitting or absorbing particles of light (photons) as it goes. Once we know the rules governing how electrons move around, we can understand the behaviour of atoms and molecules.

There's a nice analogy between particle physics and chess that illustrates this point. Suppose you do not know the rules of chess – well, you could figure them out by watching people play. It wouldn't take you too long to identify the different pieces and, with careful observation, you could also figure out the legal moves (though *en passant* might take a while to discover). Particle physics is just like this – we are trying to learn the rules of the game as best we can by observing nature. Of course, knowing the rules of the game isn't the same as playing like a Grandmaster.

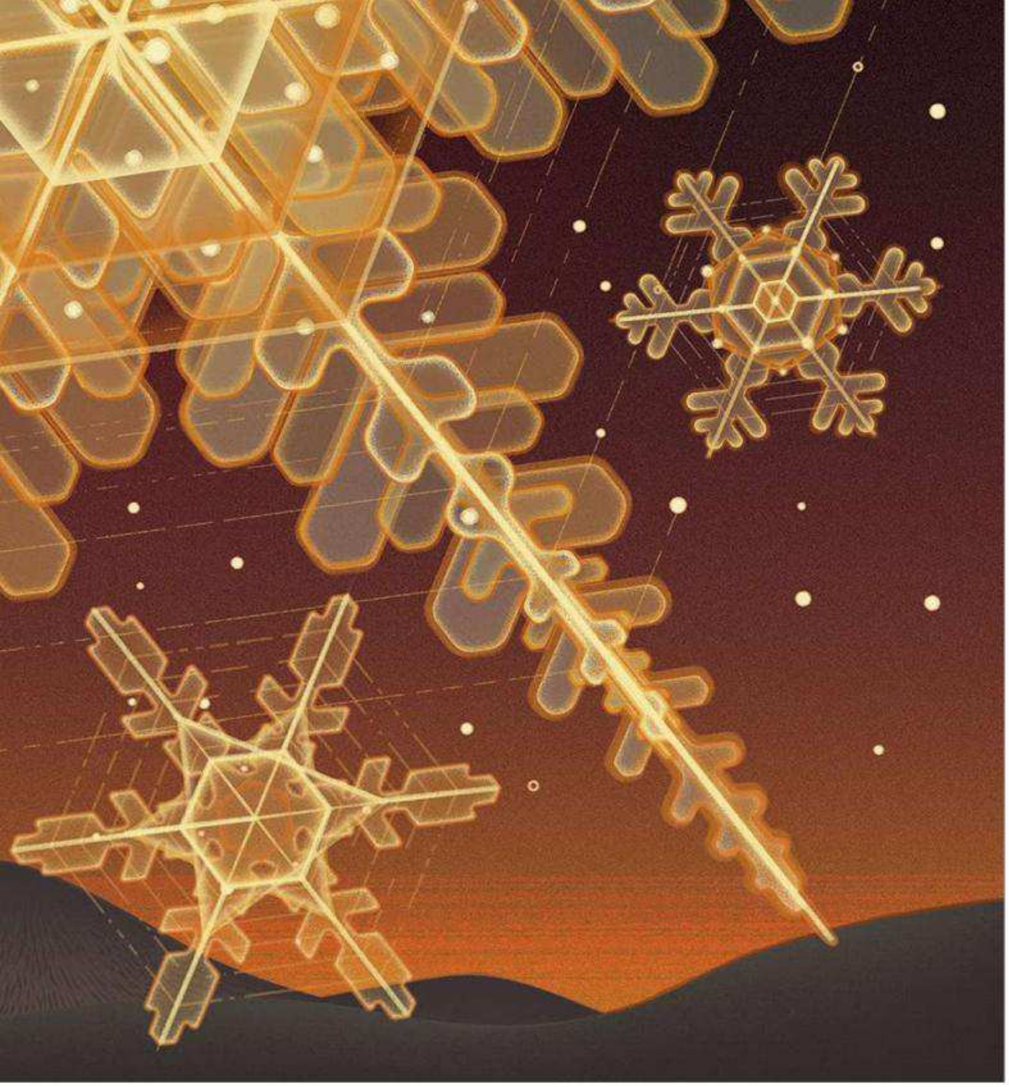
Perhaps it is necessary to encode all of these laws in huge books that fill entire libraries: giant catalogues of intricate detail. Or perhaps everything can be encoded on the back of an envelope. Because, as it turns out, the fundamental laws of nature are simple.

### NATURE'S MIRROR

Take a look at 'The key idea' (right). It illustrates how symmetry can play a profound role in shaping our understanding of the world. In the case of a snowflake, symmetry allows us to draw the entire snowflake even if we're initially shown only one half of it. Symmetry is also the main reason why we find snowflakes beautiful. Remarkably, exactly the same beauty is present in the mathematics governing the rules by which particles move around. Unlike snowflakes, this is not something that can be seen directly, because it isn't the symmetry of a shape. Instead, it is a more abstract symmetry, called 'gauge symmetry', that is encoded into mathematical equations.

To appreciate this, we can take a look at the equations, though you don't need to be good at maths to appreciate the point we're about to make. Let's suppose that we can write down the equations governing how particles that never interact with one other behave. It is possible to formulate these equations without too much trouble because Einstein's Special Theory of Relativity (see page 30) more or less dictates what to write. After this first step, we will have the equations to describe a very boring universe, which is nothing like the one in

ILLUSTRATION: SAM CHIVERS



which we live. For example, it might contain electrons and nothing else, so nothing would stick together and atoms would not exist. The key piece of maths describing such a universe is illustrated below 'The key idea'. You can appreciate just how simple it is (it easily fits on the back of an envelope).

Now here comes the brilliance of symmetry. If we demand that our equations should have a gauge symmetry, then we are absolutely forced to write down the stuff in red on the right-hand side. The amazing thing is that the stuff in red is what determines the way particles hop and branch. In other words, starting from a boring universe where nothing interacts, symmetry delivers a set of rules that dictate how particles interact with each other.

For example, gauge symmetry tells us that we must allow for the existence of photons, and it tells us that electrons hop around with the possibility to emit or absorb these photons. That's because without photons it isn't possible to make the maths symmetric. Viewed this way, photons are a consequence of the symmetry. This really is exactly the same as saying that, starting from a picture of half a snowflake, we can use symmetry to draw an entire snowflake. As far as anyone can tell, all of the elementary particles interact with each other in ways determined by gauge symmetry.

So why are the equations governing the fundamental rules of nature so simple? Good question. We don't yet know the answer. Whatever the reason, these rules lie behind all natural phenomena, from the colour of a rose to the burning heart of a star.

**Jeff Forshaw** is professor of particle physics at the University of Manchester. He has co-authored three popular science books with Brian Cox.

**Brian Cox** is a BBC TV and radio presenter, and a professor of particle physics at the University of Manchester, and the Royal Society professor for public engagement in science.



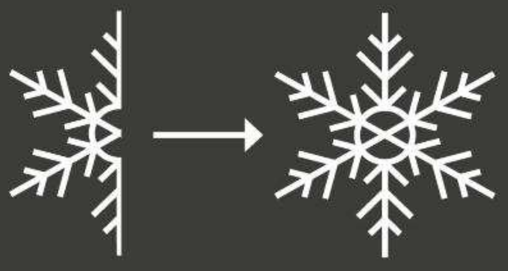
### THE KEY IDEA

## SYMMETRY SHAPES OUR UNIVERSE

Symmetry is helpful because it allows us to complete the picture of a snowflake even though we only have half a picture. The same idea is relevant when it comes to writing down the mathematical equations that govern how the elementary particles of nature behave.

Just like with the snowflake, a mathematical symmetry called 'gauge symmetry' means that the maths coloured in red can be written down starting with the maths in white. Remarkably, these red parts are entirely capable of explaining the interactions between the elementary particles.

The Greek symbol ψ represents the particles of nature (those in the first three columns of the Standard Model, such as quarks, electrons and neutrinos). The term on the left describes a world in which particles move around without any interactions at all, while those in red encode the branching rules of the particles. For example, the terms involving the W and B symbols specify the rules for emitting or absorbing photons and W and Z bosons, while the term involving the G symbol specifies the rule for emitting or absorbing gluons.



$$\bar{\psi} i \partial\!\!\!/ \psi \rightarrow \bar{\psi}(i \partial\!\!\!/ - g\tau \cdot W - g'YB - g_s T \cdot G)\psi$$

EXPLAINED IN 10 MINUTES

# QUANTUM PHYSICS

Even Nobel prize-winning physicists are baffled by this tricky subject. Here we reveal why quantum physics is relevant to all our lives

WORDS: **JOHN GRIBBIN**

**WHAT IS QUANTUM PHYSICS FOR?** Quantum physics may seem like a pretty esoteric topic with no everyday practical value, but that's far from being the case. Quantum physics is the science you need to understand the behaviour of atoms, electrons and light. It therefore underpins the workings of microchips and lasers, among other things. The chemical bonds that hold strands of DNA together, and which enable the double-stranded molecules of the famous helix to unzip and make copies of themselves, operate purely in accordance with the laws of quantum physics. Quantum physics is the science of life: it doesn't get much more basic than that!

### WAVE, PARTICLE OR BOTH?

The understanding of physics that scientists had reached by the end of the 19th Century is now called 'classical physics'. It describes the behaviour of the material world in terms of the laws discovered by Isaac Newton, and it describes the behaviour of light and other electromagnetic radiation (everything from radio waves to gamma rays) in terms of the wave equations of James Clerk Maxwell.

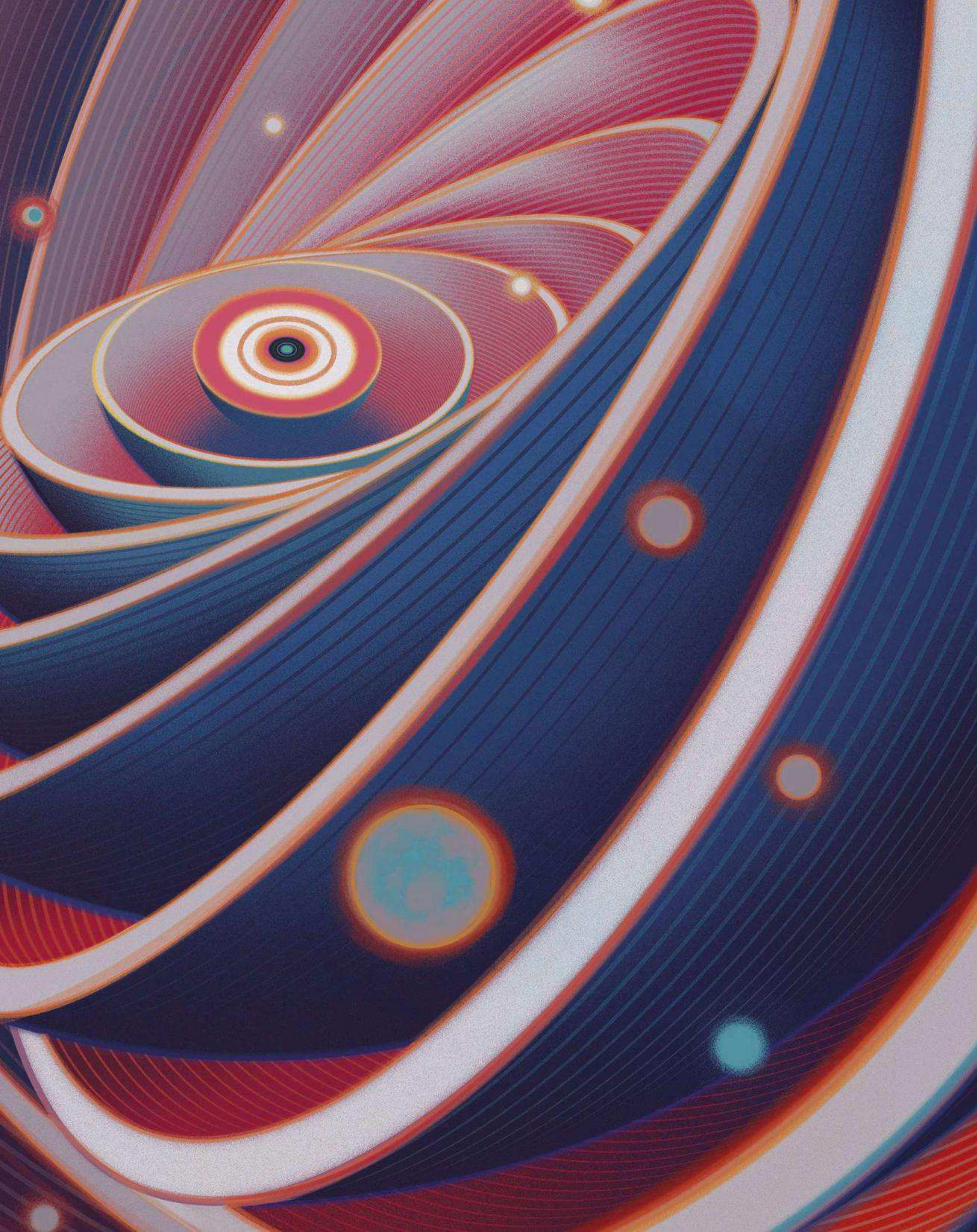
Crucially, in the world of classical physics, waves are waves and particles are particles. They interact with one another – as when an electrically charged, jiggling electron emits radio waves – but they always retain their identity. Even the General Theory of Relativity (like its simpler cousin the Special Theory of Relativity) counts as a classical theory, because it retains this distinction between waves and particles, and preserves the idea that changes happen in a continuous fashion.

Quantum physics overturns all of that. The first clue that something other than classical physics was needed came when Max Planck found that he could only explain some aspects of the behaviour of light (such as the nature of so-called black body radiation – see Jargon Buster on page 25) by treating light as being made up of particles, not a continuous wave. But other experiments still showed light behaving as a wave! Then it was discovered that electrons, which classical physics said were particles, behaved in some circumstances as if they were waves. Wave-particle duality, as it became known, lies at the heart of quantum physics.

### DOES QUANTUM THEORY RULE?

Wave-particle duality is not the whole story of the split between classical physics and quantum physics. In the world of classical physics,

ILLUSTRATION: SAM CHIVERS



a particle such as an electron has a definite position in space, and is moving in a definite direction. As long as you make allowance for all the forces it encounters along the way, you can calculate everything that will ever happen to it. This applies to all particles. The classical world is said to be 'deterministic' because once you know where everything is and where it is going, you can work out the entire future and the entire past. Both are determined by the way things are now, which doesn't leave very much room for free will! This is sometimes called 'Newton's Clockwork Universe'.

But according to quantum physics, an electron is never located at a precise place (because of its wave nature), and it is never sure where it is going. This is the 'uncertainty principle' discovered by Werner Heisenberg, who found there is a trade-off. Quantum objects can either have a relatively well-defined position and a poorly defined direction, or a well-defined direction and a poorly defined position. But they can't have both. It's the price of free will.

This ties in with another key quantum physics idea – probability. You can never say precisely where a quantum entity is or where it is going, but you can use the rules of quantum physics to work out probabilities, such as the probability that an electron will follow a certain trajectory, or the probability that a sample of radioactive material will decay and spit out a particle within a certain time.

**WHAT IS A QUANTUM?**

A quantum is the smallest amount of something that it is possible to have. The smallest amount of light you can have, for example, is a particle called a photon. If you have a bright light, there are many photons streaming outwards. But as you turn the light down, there are fewer and fewer photons. Eventually, there are so few photons that they can be detected one at a time. Astronomers see this happening when they build up images of very faint objects using long exposures of charge-coupled devices (CCDs). When atoms emit light, they do so by rearranging their electrons to radiate energy. Like a ball bouncing down a staircase, the electron jumps from one energy level to another inside the atom, and a photon is emitted. This jump is known as a quantum leap – the smallest change it is possible to make (something to remember next time you see the term used in advertising).

**Like a ball bouncing down a staircase, the electron jumps from one energy level to another inside the atom**

**CAN WE SEE QUANTUM EFFECTS?**

The definitive demonstration of quantum effects was carried out by a Japanese team in the 1980s. They took the classical experiment which 'proves' light is a wave and adapted it to electrons. The traditional experiment involves sending a beam of light through two slits in a cardboard screen to make a pattern on another screen on the far side. Like ripples on a pond, the waves started to spread out from the two slits and interfered with one another to make the distinctive pattern. In their variation on the theme, the Japanese team fired electrons, one at a time, through an equivalent setup onto a screen like a television screen, where each electron made a single spot as it arrived, showing that it was a particle. But as hundreds of electrons were fired through the experiment,

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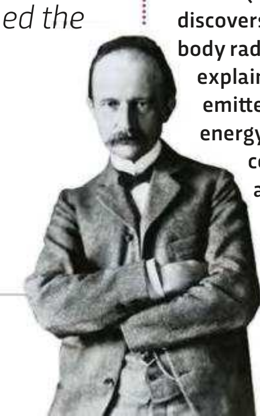
## TIMELINE

*The big breakthroughs that defined the world of quantum physics*

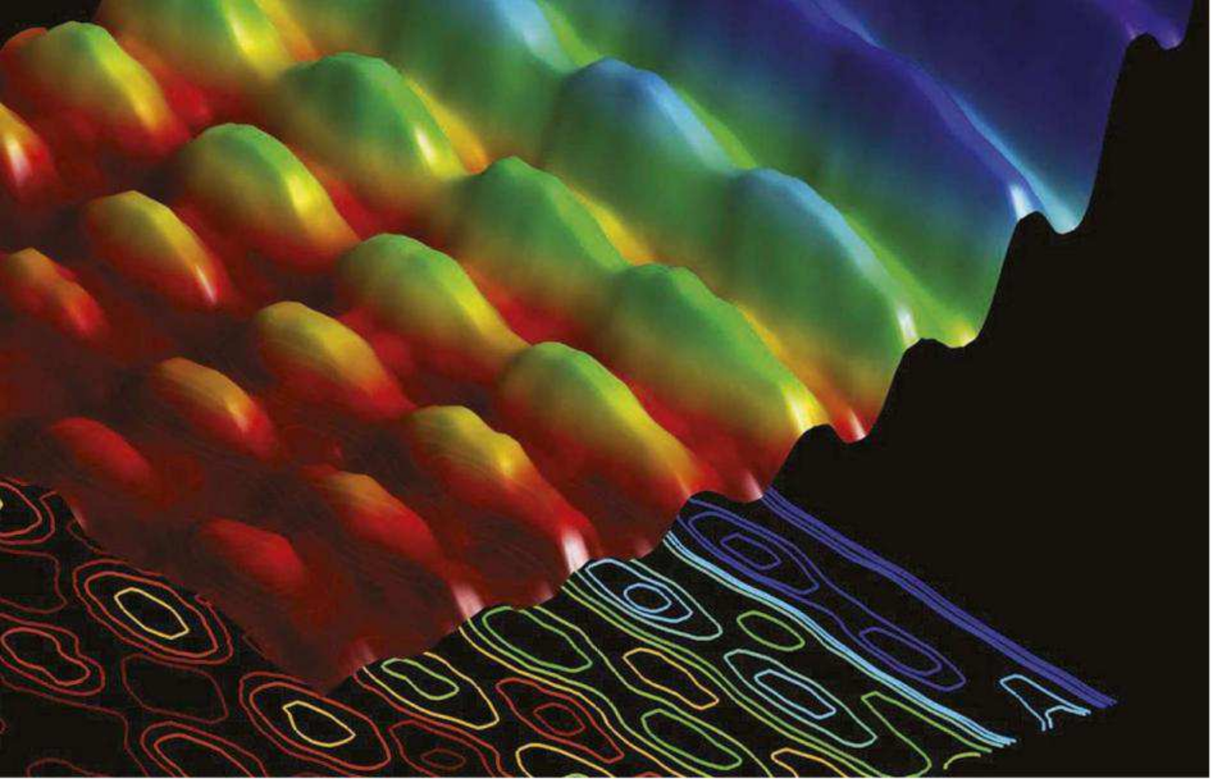
**1900**

German physicist Max Planck (1858-1947) discovers that black body radiation can be explained if light is emitted in packets of energy – photons. This conflicts with the accepted idea that light is a wave.



**1905**

German physicist Albert Einstein (1879-1955) explains the photoelectric effect, in which light falling on a metal surface makes photoelectrons jump out of the surface.



The first ever photograph of light behaving as a wave and a particle was released in March 2015

one after another, the pattern of spots that built up was an interference pattern, proving that electrons are waves.

Don't worry if you find your mind boggled by this. The US physicist Richard Feynman used to say that "nobody understands quantum physics" – and he had a Nobel Prize for it.

**ARE THERE PRACTICAL APPLICATIONS?**

Applied quantum physics is everywhere around us. Computer chips, including the ones in your smartphone, are designed using quantum physics and operate on quantum principles. The lasers used to read Blu-ray discs operate on quantum principles that were first worked out by Albert Einstein over 100 years ago. Physicists have developed tools known as superconducting quantum interference devices, or SQUIDs, in which electron waves travel round a ring of

## JARGON BUSTER

**BLACK BODY**
An object that is a perfect absorber of radiation is called a black body, hence the name. But if a black body is hot, it becomes a perfect emitter of radiation. So, paradoxically, the Sun is an almost perfect black body radiator.

**DIFFRACTION**
This is the process by which waves can bend around corners or spread out in all directions from a small hole or slit.

**DUALITY**
This is the way that quantum entities seem to be both particle and wave. Light 'waves' are associated with particles called photons; electron 'particles' are associated with waves.

**ENERGY LEVEL**
A quantum state, for example in an atom, that is associated with a particular energy. Electrons in atoms will occupy specific energy levels.

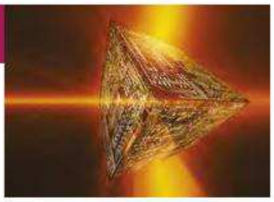
**QUANTUM LEAP**
The change of a quantum system, such as an electron in an atom, from one energy level to another. This happens without the system (electron) passing through any in-between state.

**SUPERPOSITION**
This is when a quantum system exists in a mixture of states. For example, an electron has a property called spin. On its own, the electron is in a superposition of spin up and spin down. It only 'collapses' into one state when it interacts with something. This is linked to the idea of quantum probability – there is a 50:50 chance of finding the electron in either state.

### 1913
Danish physicist Niels Bohr (1885-1962) explains the spectrum of light radiated by atoms in terms of electrons jumping between fixed energy levels, like steps on a staircase, inside the atom. This is the 'quantum leap'.

### 1927
Clinton Davisson and George Paget Thomson (pictured) share a Nobel prize for independently discovering that electrons can be diffracted like waves, confirming wave-particle duality.

### 1932
While studying cosmic ray tracks, US physicist Carl Anderson (1905-1991), sees the trace of a particle like an electron but with a positive charge. It is the positron, an antiparticle.



### 1985
David Deutsch (1953-) claims it might be possible to make a true quantum computer that could carry out certain tasks faster than a conventional one.

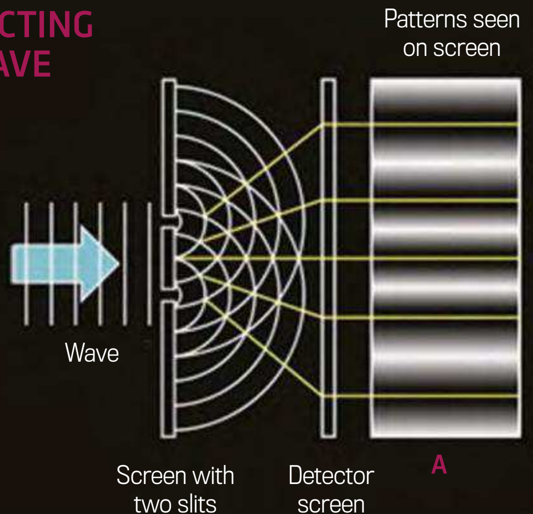
## THE KEY EXPERIMENT

In the 18th Century, debate raged as to whether light was a wave or a particle. But in 1803, English scientist Thomas Young showed that, when light is passed through two slits onto a backboard, an interference pattern appears. This is similar to what's seen when two sets of similarly generated waves collide in water (fig A). Light, he deduced, must be a wave. In the early 20th Century, however, Einstein and others demonstrated that light can also be seen as a stream of particles, called photons.

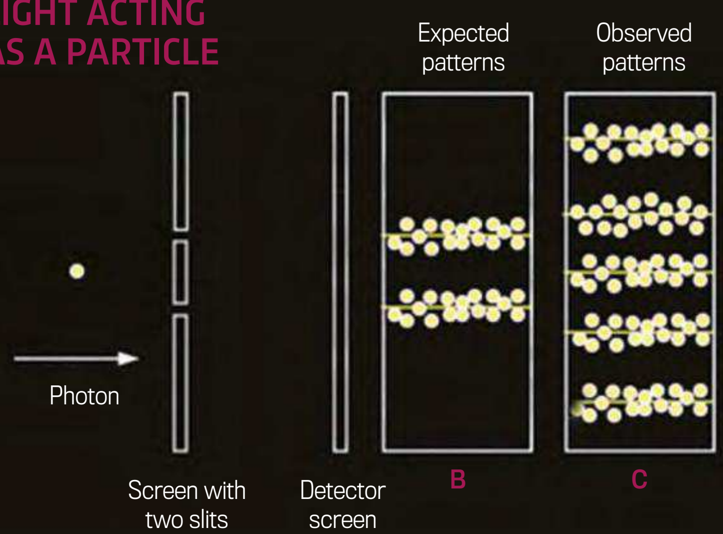
This is where things get tricky. When individual particles are sent one at a time through a double slit, as in Young's experiment, they should 'pile up' in two bands (fig B). Photons don't, though: even if you send photons through the double slit individually, an interference pattern is observed (fig C). Just to complicate matters, if you monitor which slit each photon is going through, the interference patterns are replaced by two bands. The same applies to other fundamental particles, such as electrons.

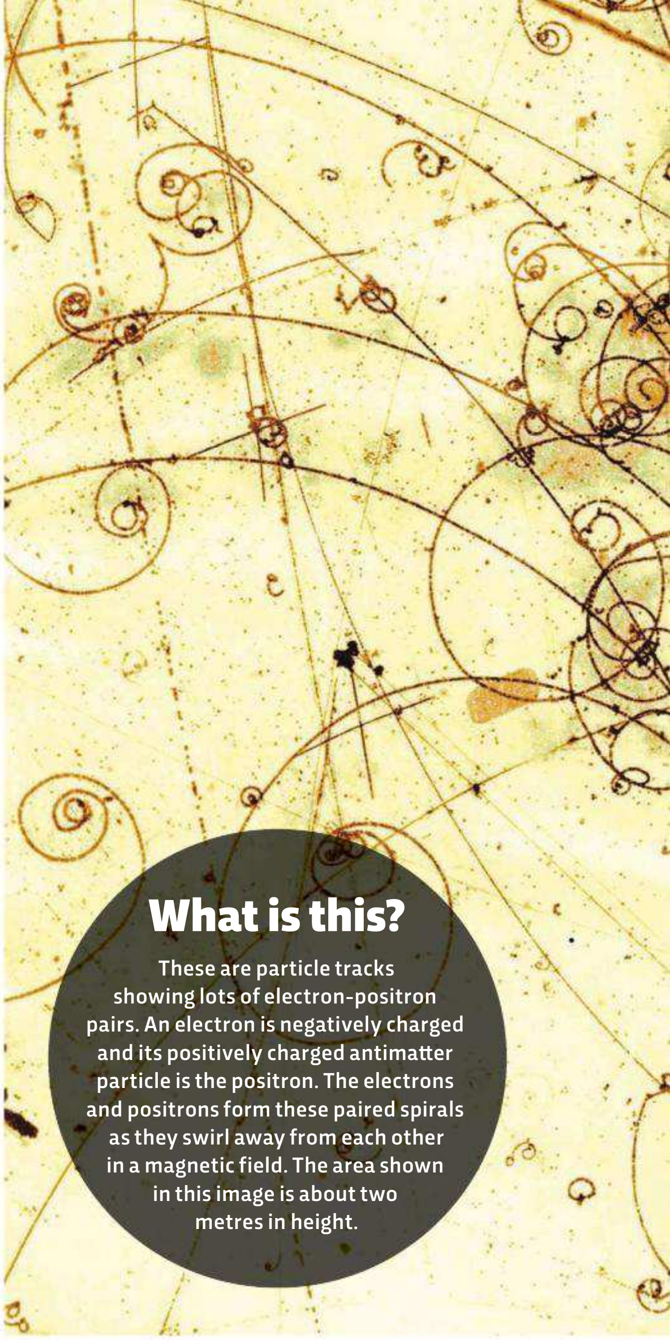
This is the mind-bending world of quantum physics, where 'wave-particle duality' is common and where the mere act of observing can affect the outcome an experiment.

### LIGHT ACTING AS A WAVE




### LIGHT ACTING AS A PARTICLE



### What is this?

These are particle tracks showing lots of electron-positron pairs. An electron is negatively charged and its positively charged antimatter particle is the positron. The electrons and positrons form these paired spirals as they swirl away from each other in a magnetic field. The area shown in this image is about two metres in height.

metal about the size of a wedding ring. These are supersensitive detectors of magnetic fields, and are used in many different applications such as MRI scanners. The most exciting application of quantum physics today is in the new field of quantum computing. Ordinary computers are based on switches that can be either on or off (0 or 1); in contrast, a true quantum computer has switches (single atoms or electrons) that can be both on and off at the same time. This is a so-called superposition, which makes the computer immensely more powerful.

#### HOW DOES QUANTUM PHYSICS EXPLAIN THE ENERGY OF THE SUN?

Stars like the Sun release energy as a result of a process called nuclear fusion. At its simplest,

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## A true quantum computer has switches that can be both on and off at the same time. This is a so-called superposition

inside the Sun two protons (hydrogen nuclei) come together and fuse, then combine with other particles to make nuclei of helium. The helium has less mass than the particles that went into it, so energy is released in line with Einstein's famous equation, $E=mc^2$. Astronomers are able to figure out how hot the interior of the Sun must be in order to hold itself up against gravity.

But this then led to a puzzle. As protons are positively charged, they repel each other and have to be moving very fast before they will collide and stick together. Classical physics said that the interior of the Sun is not hot enough for this to happen.

Quantum physics provided the explanation. When two protons are close together, but not close enough to touch according to classical theory, quantum uncertainty means that there is a probability that they might actually touch. Another way of understanding this is to think of the protons as waves, reaching out to each other.

Either way, the result is that the protons can fuse. They are said to tunnel through the barrier of classical electrical repulsion.

### WHAT IS ANTIMATTER?

One of the strangest predictions of quantum physics is that for every type of particle, there should be an antiparticle that has its key properties reversed. The electron, for example, has a negative charge, while its antiparticle, the positron, has positive charge.

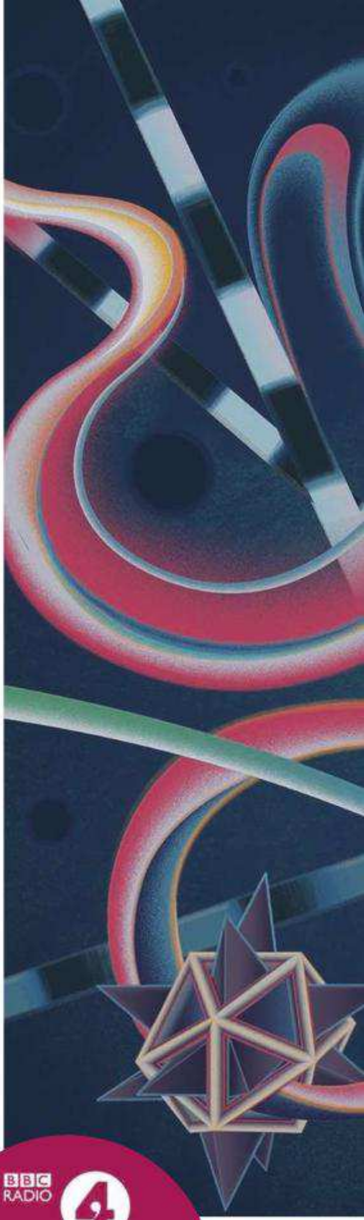
The physicist Paul Dirac was the first person to take this seriously, but when he published the idea in the 1920s he cautiously suggested that the required positive particle might be the proton, the only other particle known at the time. But in 1932 the physicist Carl Anderson discovered the tracks of positively charged particles with the same mass as electrons in a device known as a cloud chamber. This breakthrough earned him a Nobel prize.

Dirac had been more correct than he had realised himself. It turns out that particle-antiparticle pairs (such as an electron and a positron) can be made out of pure energy in line with Einstein's equation, but when a particle and its antiparticle meet they annihilate each other in a puff of gamma rays.

**Dr John Gribbin** is a science writer and Visiting Fellow in Astronomy at the University of Sussex.

Jeff Forshaw and Brian Cox
**EXPLAIN THE UNIVERSE**

# THE QUANTUM WORLD



## How subatomic anarchy gives rise to everything we see in our daily lives

WORDS: **JEFF FORSHAW AND BRIAN COX**

The future is inherently uncertain. As we discussed on page 20, we know that particles can hop around. But it's impossible to predict exactly what they will do next. What we can know is how likely they are to do a particular thing. For example, if we know that an electron is 'over here' at one particular moment then we can use mathematics to calculate how likely it is to be 'over there' at a later time. In other words, the best we can do is compute probabilities. This is not a feature of human ignorance – rather it is a feature of the Universe that the future is inherently uncertain. So how do we calculate these probabilities in quantum physics? This is where the fun really starts.

Let's plunge straight in and consider a specific example. For this, you need to look at the four graphs (top right). These show four different ways in which two electrons can travel to the points X and Y. In the top-left graph, one electron starts its journey from the upper dot on the left and the other starts its journey from the lower one. The first electron hops to point A where it does something interesting – it emits a particle of light (called a photon and denoted by the wavy line). The photon then hops from A to B, while the electron continues its journey and hops from A to X. The journey of the second electron is also interesting. It starts by hopping to point B where it absorbs the photon emitted by the first electron. After that, it hops onwards to point Y. Although this might seem quite unfamiliar, the rules of the game are really rather simple: electrons can hop from one place to another and they may or may not emit or absorb photons. You can use these simple rules to draw your own graphs of how the electrons might hop and branch their way to points X and Y.

BBC RADIO 4

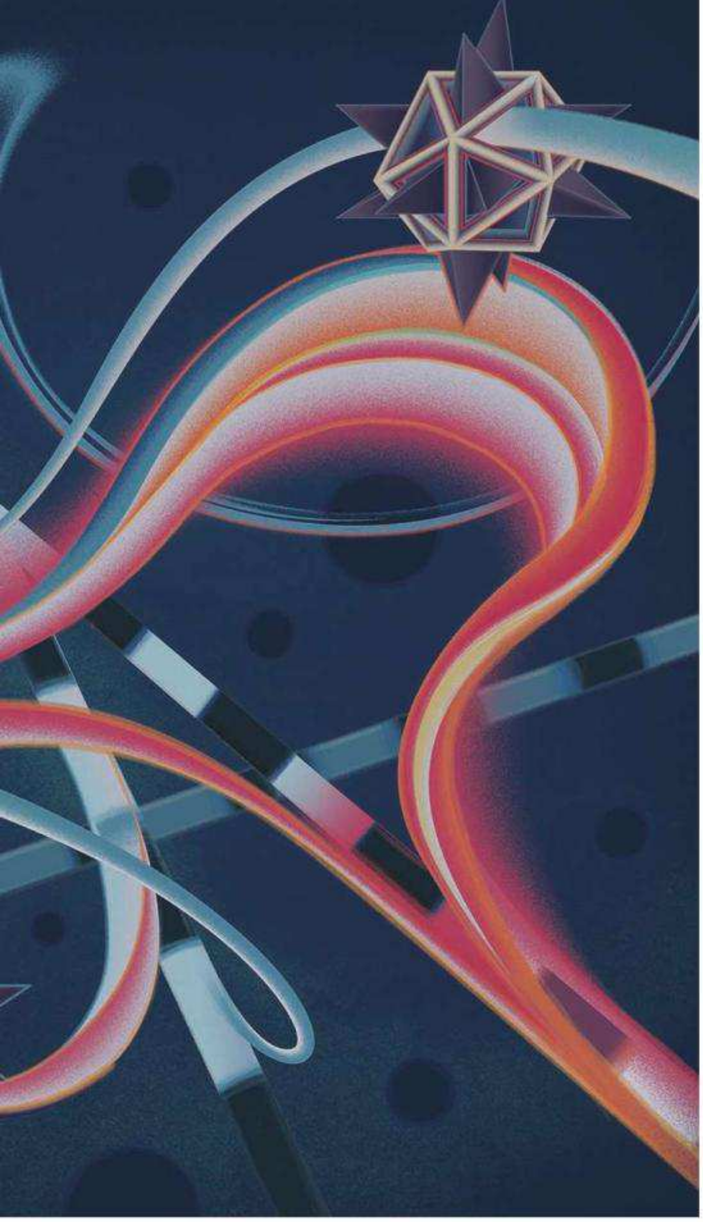
Listen to an episode of *The Infinite Monkey Cage* about quantum physics at ***bit.ly/monkeycage***

### RESTLESS PARTICLES

Graphs like these are called Feynman diagrams (after the US physicist Richard Feynman) and they describe how particles interact with each other. But nice pictures don't amount to very much – we need to use them to help us calculate the probability that the electrons will end up at the specific points, X and Y. Remember, calculating the probability that something happens is the aim of the game in quantum physics.

Feynman diagrams can be translated into mathematics. Specifically, for every hop an electron makes (so for every straight line

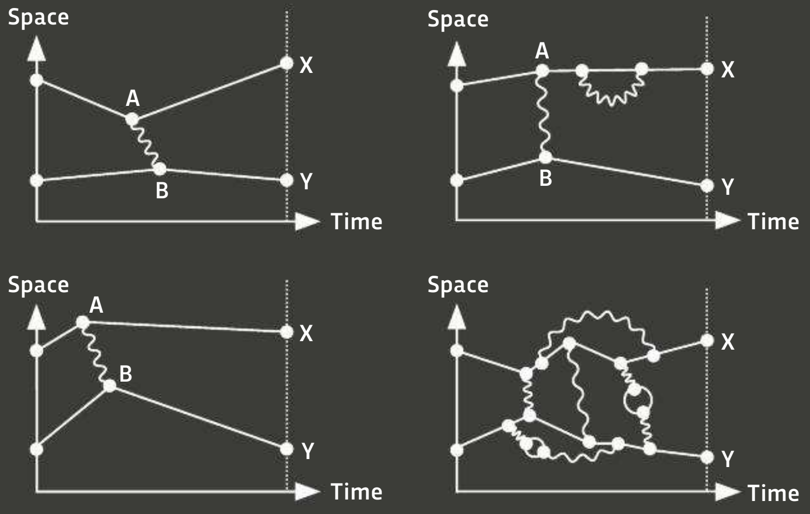
**They're key to understanding how semiconductor devices work – the basis of our tech**



THE KEY IDEA

## EVERYTHING THAT CAN HAPPEN DOES

**These graphs show four different ways in which two electrons can travel from their initial positions (denoted by the two dots on the left of each picture) to the points marked X and Y. Along the way, they can exchange a photon (or photons), denoted by the wavy lines. For each, it is possible to compute a number, and then we add together all of these numbers to compute the probability that the particles will actually arrive at X and Y. We've drawn four graphs, but there are infinite possibilities: the electrons must travel by *every* possible route in order to arrive at their destination.**




in a Feynman diagram) we can assign a particular number (the size of the number depends on how big the hop is). Similarly, every time an electron emits or absorbs a photon, there is a number. All of these numbers should be multiplied together to obtain one final number for each graph. In other words, we can calculate a number for each of the four graphs. Add those numbers together and you get the probability of finding one electron at X and the other at Y. (Actually, it's slightly more complex than this but that's the basic idea.)

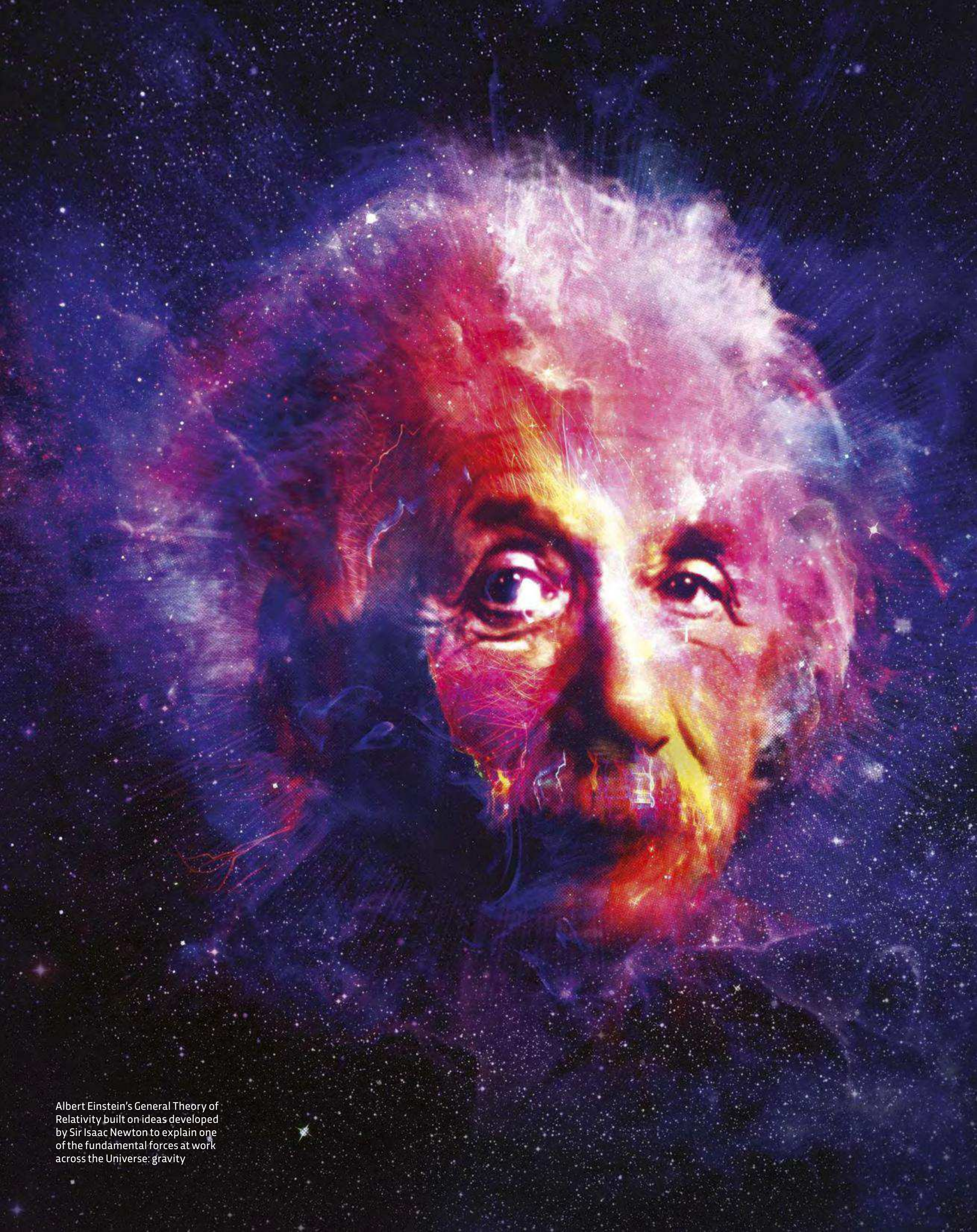
As we have seen, the rules of quantum physics are quite simple. Once we have the rules for how electrons and photons can jump around, we can draw Feynman diagrams and compute probabilities that can be tested in experiments. And these are not esoteric calculations either: they allow us to compute how atoms behave, which is crucial for understanding chemistry. They are also key to understanding how semiconductor devices work, and these form the basis of today's technology. In other words, quantum theory underpins our modern world.

The trouble is that nature's quantum rules lead to a picture of the microworld that is pretty much impossible to imagine. But it seems that this is how the world actually behaves – the Universe is far richer than our imagination can grasp. The bottom line, then, is that although the rules might be weird, they can be used to make precise mathematical predictions concerning the real world.

ILLUSTRATION: SAM CHIVERS

**Jeff Forshaw** is professor of particle physics at the University of Manchester. He has co-authored three popular science books with Brian Cox.

**Brian Cox** is a BBC TV and radio presenter, and a professor of particle physics at the University of Manchester, and the Royal Society professor for public engagement in science.



Albert Einstein's General Theory of Relativity built on ideas developed by Sir Isaac Newton to explain one of the fundamental forces at work across the Universe: gravity

# HOW GRAVITY WORKS

EVERYONE KNOWS THAT WHAT GOES UP MUST COME DOWN. BUT WHY? GRAVITY, IT TURNS OUT, IS FULL OF SURPRISES...

WORDS: **BRIAN CLEGG**

Without gravity, we wouldn't exist. It provides the force that keeps us on Earth's surface and Earth in orbit around the Sun. It's responsible for the formation of the Solar System and it's the gravitational attraction of all the material in the Sun that makes nuclear fusion occur, giving us heat and light. Yet despite its ubiquity, gravity is one of the most mysterious forces in the Universe.

**WHAT IS GRAVITY?**

As one of the four fundamental forces of nature (alongside electromagnetism and the strong and weak nuclear forces) gravity is hugely influential. It's a property of matter, of stuff. In a nutshell: all matter is attracted to all other matter. The more matter there is, and the closer objects are to each other, the bigger that attractive force. And unlike electricity and magnetism, which can either repel or attract, gravity always pulls things together.

ILLUSTRATOR: ANDY POTTS

**WHAT WAS NEWTON'S THEORY OF GRAVITY?**

Newton famously stated that he didn't have a hypothesis for how gravity worked. Instead, his starting point for describing it in action was the idea that gravity was universal – that the same thing that made an apple fall from a tree kept the Moon in orbit. With this concept, a collection of astronomical data and some thought experiments, Newton was able to show that just three things influence the gravitational attraction between two objects: the mass of each object and the distance between them.

Although he never wrote it out in this form, his theory would show that gravitational attraction follows an inverse square law. The pull of gravity can be calculated by multiplying the masses of two objects and then dividing by the square of the distance between them. So the attractive force of gravity goes up as either of the objects' masses increases, or as they get closer. This simple relationship was enough to explain almost all of the movement of

the Moon and planets, and would be all that NASA needed to calculate a safe trajectory for the Apollo mission to the Moon.

### WHAT IS THE EQUIVALENCE PRINCIPLE?

The equivalence principle is based on what Albert Einstein described as his "happiest thought". This was that "if a person falls freely, he won't feel his own weight". In other words, acceleration and gravity are exactly equivalent and indistinguishable.

We see this happening on the International Space Station. The pull of gravity at the station's orbital distance from Earth is around 90 per cent of that on the surface. The reason it stays up there is because it's constantly falling towards Earth. You might expect it to crash into Earth's surface, but it's also moving sideways at just the right speed to keep missing – that's what being in orbit involves.

The equivalence principle shows that acceleration cancels out an object's weight. Einstein made the leap from his happy thought to suggest that acceleration and gravity are, in effect, the same thing. And this inspired his General Theory of Relativity, which explains how gravity works.

**Einstein was able to show that bodies with mass – anything from an atom to a star – warp space and time**

### WHAT WERE EINSTEIN'S IDEAS ABOUT GRAVITY?

From his equivalence principle, Einstein was able to show that bodies with mass – anything from an atom to a star – warp space and time. And it was this warping that explained something Newton hadn't been able to show: why gravity can operate at a distance. Larger objects produce larger warps in space-time, drawing in nearby objects and forcing them into curved trajectories. But even smaller bodies have an effect – each of us exerts a tiny gravitational force on the objects around us.

Because he was taking a different approach to Newton, Einstein had to use a different kind of mathematics, one that he initially knew little about: the mathematics of curved space. And he had to take into account various secondary effects that Newton had no reason to suspect existed, such as the surprising discovery that gravity has an effect on itself.

Einstein's equations of General Relativity do everything Newton's equation does, but because they describe the way that anything with mass warps space and time, they can do much more.

### WHAT EXACTLY IS GENERAL RELATIVITY?

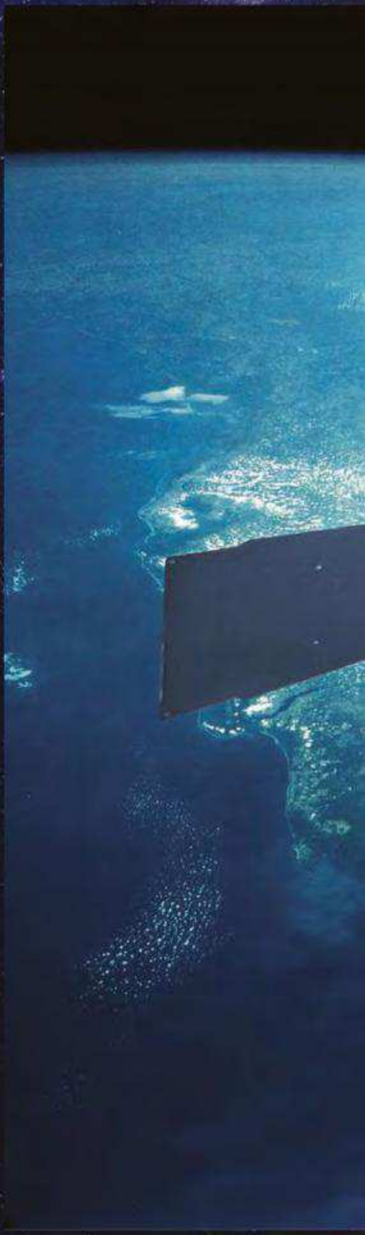
The General Theory of Relativity describes how mass and energy cause space-time to warp, giving rise to what we perceive as gravity. This theory built on Einstein's earlier Special Theory of Relativity. Both theories are based on the idea that the laws of physics act in the same way everywhere and that the speed of light is constant. From this starting point, Einstein deduced that as everything is moving relative to everything else, different viewers see the same event differently. This is where the theory gets its name.

### WHAT PROOF DO WE HAVE FOR EINSTEIN'S THEORY?

There's lots of evidence for General Relativity. Before Einstein's theory, astronomers had struggled to explain an aspect of Mercury's orbit called its precession, where its point of closest approach to the Sun gradually changes position. Newton's equations couldn't explain it, but Einstein's work did.

What's more, the idea that gravity was caused by a warp in space and time was also testable, because it meant that (for instance) light passing close to a massive body should travel in a curve through the warped space that the body creates. This was first observed with light passing close to the Sun during a total eclipse in 1919 and has since been seen when distant galaxies act like lenses, bending the path of light behind them.

Another of the predictions of Einstein's equations is that being near a massive body ➔



NASA lauched the Gravity Probe B satellite in 2004 to test how much Earth's gravity warps the surrounding space-time

GETTY X4, SCIENCE PHOTO LIBRARY, NASA, DAN MARRONE/UNIVERSITY OF ARIZONA

# 5 WAYS
## YOU CAN SEE EINSTEIN'S THEORY IN REAL LIFE

### MASS

The 'Higgs field' accounts for only about 1 per cent of your mass. 99 per cent is due to a relativistic effect. Specifically, the quarks that compose you are moving so fast they gain mass. Without Einstein, you would weigh only about 1kg!

### SUNLIGHT

Einstein saw mass as a form of energy. As such it can be converted into other forms of energy. This is what's happening in the Sun's core, where nuclear reactions convert about 0.7 per cent of the mass of hydrogen nuclei into heat and sunlight.

### GOLD

An atom absorbs and re-emits light when an electron moves between orbits. The light's energy (colour) depends on the energy difference between the orbits. Gold should look silver, but its electrons move so fast that they gain mass, making it look gold.

### THE UNIVERSE

The distant Universe seen through telescopes isn't actually there: it's an illusion. The reason is that matter creates valleys in space-time that light from far off objects must negotiate. So our view of it is distorted, as if seen through frosted glass.

### SLOW SATELLITES

Smartphones and sat-navs calculate your location relative to GPS satellites. When they pass close to Earth, they experience stronger gravity that slows their clocks. This effect must be compensated for in order to accurately calculate your location.

## JARGON BUSTER

**INVERSE SQUARE LAW**
The gravitational force follows an inverse square law, which means gravity is inversely proportional to the square of the distance between two objects. As they get further apart, the gravitational force rapidly diminishes.

**SPACE-TIME**
In Einstein's Special Theory of Relativity, space and time are pulled together into a single concept: space-time. Objects with mass warp space-time, influencing time and space.

**PRECESSION**
The orbit of a planet does not follow exactly the same path every time, but undergoes precession, shifting its position around its host star. The precession of Mercury's orbit could not be explained by Newton's theory.

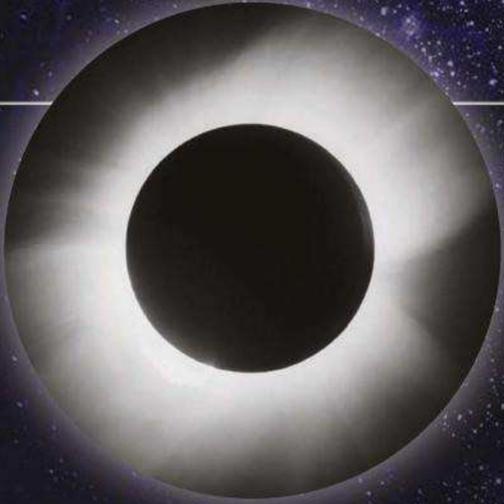
**WEIGHT**
Confusingly, we often use the units of mass for weight, but it's totally different. Weight is the force an object experiences due to gravity, so is different on Earth than it is in space.

# GENERAL RELATIVITY'S SUCCESSES

## THIS ISN'T THE FIRST TIME EINSTEIN'S FAMOUS THEORY HAS BEEN PUT TO THE TEST

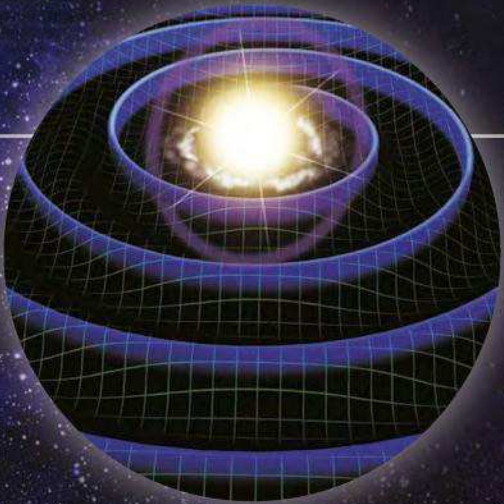
### MERCURY MYSTERY

According to Einstein, the gravity near the Sun is stronger than Newton would have predicted. This causes the elliptical orbit of Mercury to gradually change its orientation. It 'precesses', which means the planet traces out a rosette-like pattern around the Sun. Before Einstein, this was such a puzzle that it led to the suggestion that a planet – Vulcan – was tugging on Mercury.



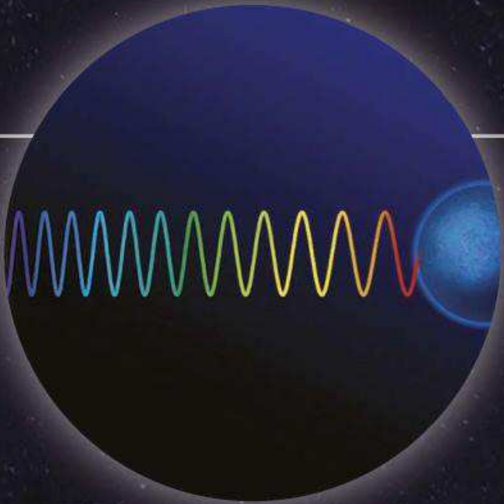
### TIRED LIGHT

As light climbs out of the valley in space-time around a massive object like a star, it loses energy. This is equivalent to a reduction in its frequency and is known as a gravitational red shift. It has been observed in the light of dense, white dwarf stars. In 1959, it was even observed in light climbing up a 22.6m tower on Earth by physicists Robert Pound and Glen Rebka at Harvard University.



### RIPPLING GRAVITY

In September 2015, 100 years after Einstein published his theory of General Relativity, the LIGO (Laser Interferometer Gravitational-Wave Observatory) detected 'gravitational waves' for the first time ever. The waves were caused by two black holes smashing together 1.3 billion light-years away, creating ripples in the very fabric of space-time.



### BENT LIGHT

Einstein calculated that the gravity of the Sun would bend the trajectory of light from distant stars by twice the amount Newton would have predicted. The only way to observe stars close to the Sun is during a total eclipse when the solar disc is blocked by the Moon. During the eclipse of 29 May 1919, the English astronomer Arthur Eddington confirmed that the positions of stars were shifted, as Einstein had predicted.

NASA X2, SCIENCE PHOTO LIBRARY X2, GETTY

slows time down: this is why we need to correct the signal from the GPS satellites that give us sat-nav.

**IS EINSTEIN'S THEORY THE WHOLE OF THE PICTURE?**
Almost certainly not. General Relativity is extremely effective when it comes to predicting the behaviour of everyday objects. But there are a few circumstances – in black holes or before the Big Bang – where the theory breaks down.

The physics of the very small is described with impressive accuracy by quantum theory, but General Relativity and quantum theory are incompatible. The assumption is that it should be possible to develop a quantum theory of gravity that would bring it in line with the other forces and still produce the same results as Einstein's theory for larger objects. As yet, the best attempts are string theory/M-theory and loop quantum gravity, but neither one has produced any usable predictions yet.

**COULD A SUBATOMIC PARTICLE CAUSE GRAVITY?**
Probably and it already has a name: the graviton. One way that quantum theory represents the transmission of a force like electromagnetism is as a flow of carrier particles called bosons (see page 16). In the case of electromagnetism, the particle is the photon. Each particle is a quantum (a chunk) of the quantised phenomenon.

So if gravity is a quantum effect, we assume that there'll be a graviton as its carrier. But don't expect one to appear at the Large Hadron Collider any time soon. A graviton is so unlikely to interact with another particle in a detectable way that as yet there's no way to spot one.

**IS THERE SUCH A THING AS ANTIGRAVITY?**
Not that we know of. Unlike electromagnetism, gravity is a one-way effect – it only attracts. We don't know any way to shield against gravity, either: it passes through everything.

One chance of discovering antigravity is that antimatter may be gravitationally repelled by ordinary matter. Scientists at CERN will soon have enough antimatter to test this out, but most physicists think it'll behave just like the normal stuff.

**WHAT DOES GRAVITY HAVE TO DO WITH BLACK HOLES AND THE NATURE OF THE UNIVERSE?**
The predictions of Einstein's theory are usually the result of solving simplified versions of his equations. One of the earliest described a compressed mass where all the matter was in a single point – a gravitational singularity. Later, it was realised that some ageing stars would be unable to resist the pull of gravity and should collapse in on themselves to form such a point, creating a black hole. The gravity in a black hole is so strong that not even light is capable of outrunning it, and although we've never seen one, indirect observations confirm that they do exist.

Similarly, General Relativity predicted that the very fabric of the Universe could expand and contract. Combined with observations, this has become the basis for our best theory on how the Universe developed: the Big Bang model. It's also General Relativity that could shed light on dark energy – the mysterious phenomenon that seems to be accelerating the expansion of the Universe.

**Brian Clegg** is a science writer. His most recent book is *Gravitational Waves*.

## WHAT WE STILL DON'T KNOW

### 1. WHY GRAVITY IS SO WEAK
It's hard to appreciate just how weak gravity is. When you pick up a pin with a magnet, for instance, the magnet is overcoming the gravitational attraction of the entire planet. Some theories suggest that this weakness is because gravity 'leaks' out into different dimensions, but we're unlikely to get a testable explanation without first devising a quantum theory of gravity.

### 2. WHEN WE'LL PRODUCE A QUANTUM THEORY OF GRAVITY
Mosts physicists will tell you it could be soon, but they've been saying that for 40 years. As yet, the main contender – string theory – and its rivals have yet to become testable theories. And that's with hundreds of people working on them. It's likely we'll succeed, but it may need a whole new theory to be developed before the problem can be cracked.

### 3. WHETHER WE CAN PRODUCE ENOUGH GRAVITY TO LIVE IN SPACE
Living things deteriorate without gravity. We can make artificial gravity by accelerating, but the only way to do so constantly without using too much fuel is to spin, and if you spin too small a craft the occupants get dizzy. Experiments with artificial gravity have been underway since a 1966 Gemini mission, but we don't yet have a realistic solution.



# THE UNIVERSAL FABRIC

**To understand the cosmos, we first need to get to grips with the nature of space and time. And when we start to do that, some strange ideas emerge...**

WORDS: **JEFF FORSHAW** AND **BRIAN COX**

Here's a strange idea: it is impossible to catch up with a beam of light. Light travels at about 300 million metres every second, but if you chased after it at 299 million m/s, it would still be receding from you at 300 million m/s, not at the 1 million m/s you might expect (strictly speaking, the light should be travelling through empty space). That crazy-sounding idea comes from Albert Einstein, and is the bedrock of his Special Theory of Relativity.

The implications of Einstein's idea are enormous. For example, it means that time does not tick at a steady rate across the Universe – in some places it ticks faster than in others, and it becomes possible for people to age at different rates depending on where they are and what they are doing.

Perhaps the most dramatic example of this is the 'twin paradox', where an astronaut departs from Earth, leaving her twin brother behind. She zips around for a bit in her super-fast spaceship and then lands back on Earth a year later, only to find that many more years have passed back home, and her brother is now an old man. This is exactly the kind of weirdness that must be true if Einstein is right – though we aren't aware of it in our everyday lives because we can't zip around fast enough, and so are tricked into thinking time is more constant than it actually is.

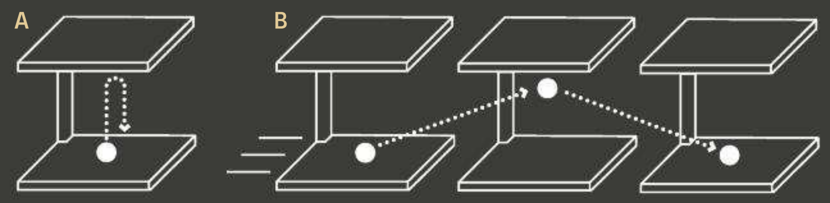
The fact that a moving clock does not tick as fast as a stationary one is actually quite easy to demonstrate. First, imagine a clock made from two parallel mirrors, between which a particle of light or 'photon' bounces back

ILLUSTRATION: SAM CHIVERS

## THE KEY IDEA

# MOTION SLOWS THE PASSAGE OF TIME

Imagine a clock made from two parallel mirrors with a photon (particle of light) bouncing between them. If the mirrors are placed the correct distance apart, the photon will take one second to make a round trip between them (A). If the clock is moving horizontally, however, the photon will trace out two sides of a triangle, travelling a greater distance (B). Since the speed of light is constant, the photon will take longer to bounce between the moving mirrors, and – from our point of view – each second on the moving clock will take longer than on the stationary clock.




and forth (see 'The key idea', above). Imagine you have one of these little clocks in your hand, and that you can watch the particle as it goes up and down, counting the bounces as a way of measuring time. Now imagine that a friend also has one of these clocks, but that she's moving horizontally.

From your point of view, her photon traces out two sides of a triangle as it bounces from one mirror to the other and back again, travelling further during each round trip than the photon in your clock.

There's nothing controversial in what we just said. Here comes the weird bit. Because, according to Einstein, the light bouncing in your friend's clock is travelling at the same speed as the light in your clock, the light in your friend's clock must take longer to bounce between the mirrors. In other words, your friend's clock is running slower than yours.

This remarkable conclusion might sound like a special feature of light clocks. But it isn't… it is a feature of all clocks. To understand why, we need to introduce Einstein's second crucial idea – an idea first introduced by Galileo Galilei in the early 1600s.

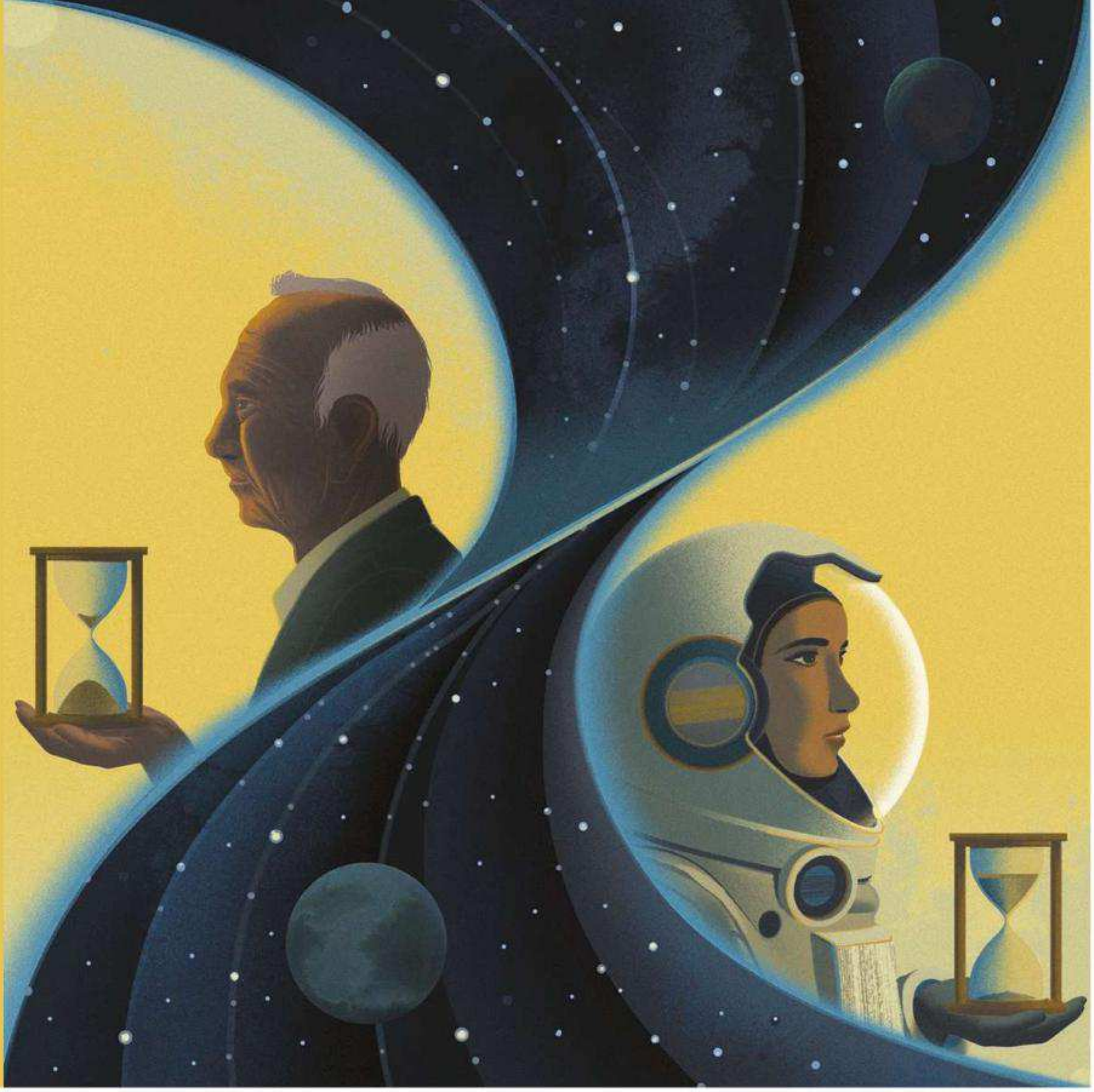
Galileo imagined a ship moving at fixed speed over a calm ocean. Inside this ship, below decks, is a host of "flies, butterflies and other small flying animals". He noted that, from observations of the creatures made only inside the ship, it would be impossible to tell whether the ship was moving or standing still. The idea that experiments and observations made in a laboratory 'at rest' give exactly the same results as those made in a laboratory that's moving uniformly is called the 'principle of relativity', and Einstein followed Galileo in assuming it to be true. According to this principle, if a moving light clock is slowed down, then so must all other moving clocks be, including our wristwatches and our heartbeats. To appreciate this point, let's suppose light clocks are actually special, and that they slow down while other types of clock do not. If this were true, a person could compare their light clock with their wristwatch and, because the light clock would be running slow, they would know that they were moving. Since this contradicts the principle of relativity, logic tells us that light clocks cannot be special.

### IT'S ALL RELATIVE

The principle of relativity also means that movement is always relative. It makes no sense to say "I am moving when I cycle down the road" – it only makes sense to say "I am moving relative to the road". This isn't as boring an observation as it sounds. A moving clock runs slow compared to one at rest, but it would be equally valid to regard the moving clock as being 'at rest' and the other clock as moving. In which case we appear to be saying that each clock runs slow compared to the other, and that sounds like nonsense. But remarkably, there is no logical contradiction here. For example, it is okay for person A to say that person B is ageing more slowly and for person B to say that it's person A who is ageing more slowly; these two statements are both true so long as A and B are in uniform motion relative to each other. Of course, A and B cannot both be younger than each other if they actually meet up for a cup of coffee. But in order to do that, one or both must accelerate or decelerate, and then the two of them will no longer be moving relative to each other.

We can use this logic to shed a bit more light on why the astronaut twin really does age less

ILLUSTRATION: SAM CHIVERS



than her Earth-bound brother. From the point of view of her brother, she is always ageing more slowly than he is because she is always moving relative to him, and because he never accelerates or decelerates (he is 'in a state of uniform motion'). This means his sister must be younger than he is when she returns.

Understanding this from her point of view is more tricky. Actually, her brother is ageing more slowly than she is during those parts of her journey where she is moving uniformly. It is only when she is accelerating or decelerating (which she needs to do in order to return to Earth) that her brother suddenly ages and this is why, when she finally returns, he is older.

### FLIGHTS OF FANCY

Andromeda is our neighbour. It is a spiral galaxy containing one trillion stars, and is situated around 2.5 million light-years from Earth. This means that light arriving in our telescopes today started its journey from Andromeda before there were any humans

**Time does not tick at a steady rate across the Universe – in some places it ticks faster**

## JARGON BUSTER

**LIGHT CLOCK**
A type of clock where light bounces between a pair of mirrors. This provides a useful way to think about Einstein's Special Theory of Relativity, which says a moving clock will run slower than a stationary one.

**TWIN PARADOX**
The puzzle that two identical twins should age at different rates depending on how they move. There's actually no paradox – Einstein's Special Theory of Relativity explains why this is true.

**NEUTRON STAR**
These astonishingly dense dead stars have a mass roughly equal to the Sun, but squeezed into the size of a city. Spinning neutron stars emit pulses of radio waves, which can be used by astronomers to test Einstein's theory of gravity.

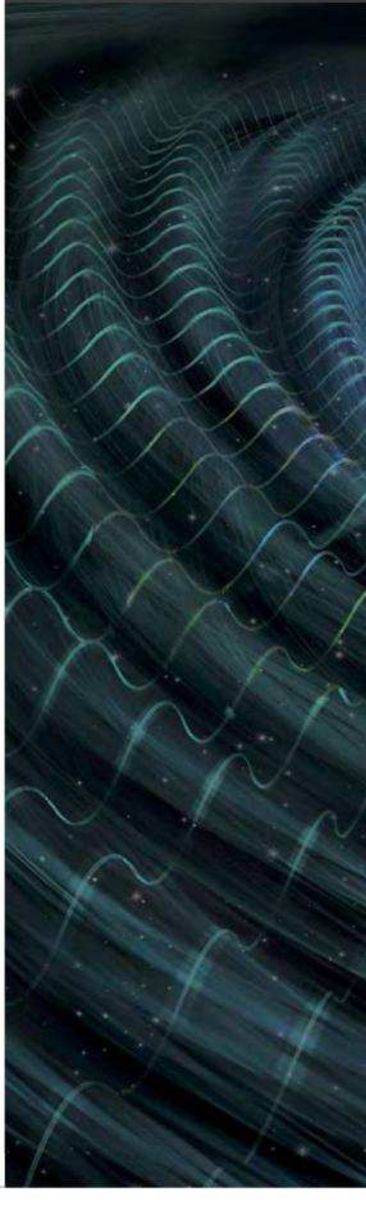
**PRINCIPLE OF RELATIVITY**
The idea that there is no way to define 'at rest' in any absolute sense. In other words, all motion is relative.

**SPACE-TIME**
Modern physics combines the three dimensions of space and the one dimension of time into this single, four-dimensional entity.

**GRAVITATIONAL WAVE**
A moving ripple in the fabric of space-time that causes lengths to change and clocks to tick at different rates as it passes by.

RIGHT: Jodrell Bank's Lovell Telescope played a part in confirming the existence of gravitational waves, and so confirming Einstein's theories

BELOW: Gravitational waves – ripples in the fabric of space and time – confirm Einstein's theory



on Earth. It also means that a space expedition travelling at the speed of light would take at least 2.5 million years to reach the galaxy, *as determined using clocks at rest relative to the Earth*. Such a long journey seems to imply that no human could ever travel to Andromeda. But that is not true, and those italicised words are the key.

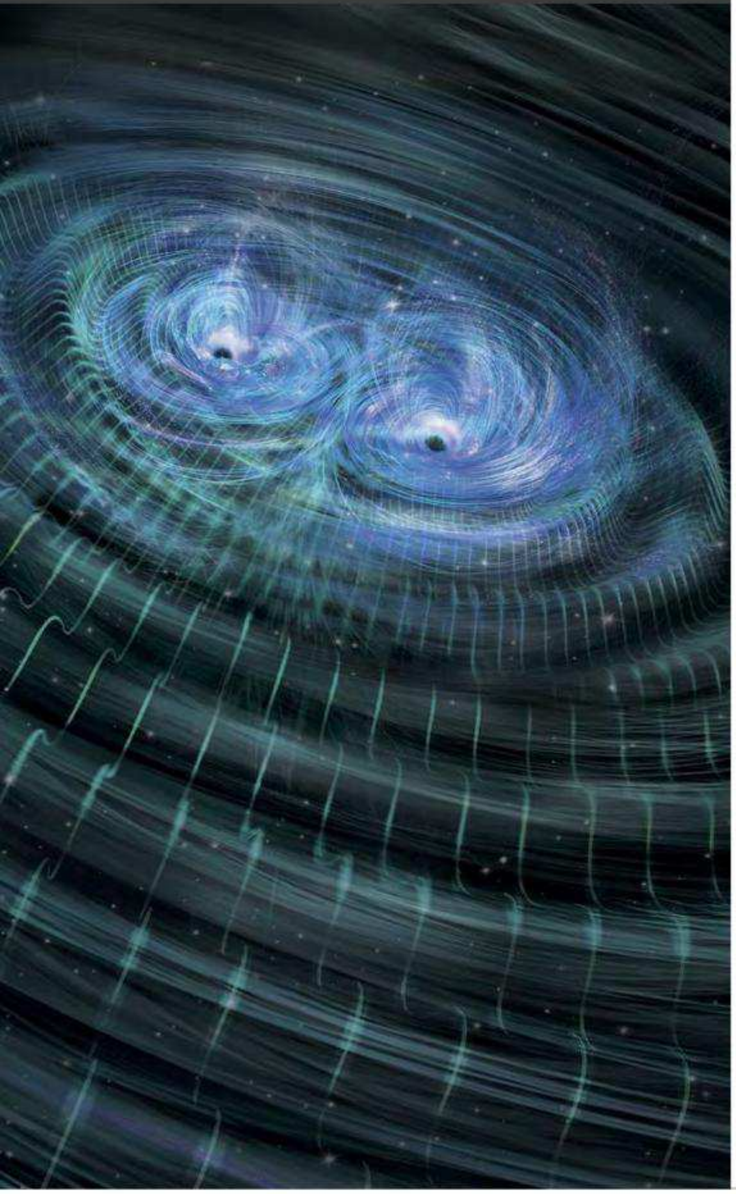
Just as with the twin paradox, the astronauts onboard the spaceship will age much more slowly than the folks back on Earth, and the faster the spaceship travels, the more this will be the case. In fact, we can work out that a spaceship travelling at 99.99999999 per cent of the speed of light could travel to Andromeda in just 50 years as measured by those on board the spaceship (and 2.5 million years as measured by people on Earth). This is a lovely result because it implies that humans can conceivably explore the cosmos. We are not forever trapped within the confines of the Milky Way – we just have to invent a spacecraft that will transport us fast enough.

Putting dreams aside, the feasibility of a 50-year-long journey to Andromeda highlights another intriguing conundrum, which again calls into question the nature of space and time. Let's think about the journey from the perspective of those onboard. For them, Andromeda is hurtling closer at nearly the speed of light. If the spaceship had to travel 2.5 million light-years, then it would take 2.5 million years to get there. But as we've just seen, it will arrive in 50 years. This implies that, from the spacefarers' point of view, the distance to Andromeda is just 50 light-years.

In other words, Einstein's theory forces us to conclude that, like time, distances in space are also subjective things. It simply does not make sense to say that "the distance to Andromeda is 2.5 million light-years." We have to add the caveat, "as determined by people on Earth."

**WHAT GOES UP…**

With his General Theory of Relativity, Einstein made the bold claim that a clock placed at sea level ticks more slowly than one placed at the top of a mountain. In other words, time passes



GETTY, SCIENCE PHOTO LIBRARY ILLUSTRATION: SAM CHIVERS

## This is a lovely result because it implies that humans can conceivably explore the cosmos

at different rates depending on the strength of gravity (which decreases as you get further from Earth's core).

We can appreciate why this might be true by calling, once again, upon the wisdom of Galileo. As legend has it, he dropped a heavy ball and a light ball from the Leaning Tower of Pisa, and confirmed that the two hit the ground at the same time. He had shown that all objects accelerate to the ground at the same rate. This feature of gravity is intriguing because it means there's no difference between doing an experiment on the Earth and doing it inside a spaceship accelerating at 1g (which is equal to the gravitational pull at the Earth's surface). In other words, the effects of gravity and acceleration are essentially the same.

So how does this link in with Einstein's ideas about gravity? Let's return again to the twin paradox. When the astronaut twin fires up her rockets and accelerates her spaceship, her experience is the same as someone who is under the influence of a gravitational pull. Since, as we've already shown, her time runs more slowly than her brother's during this part of her journey, and since her experience is identical to that of someone experiencing gravity, we can conclude that time runs slower for clocks that are under the influence of stronger gravity.

Today, Einstein's ideas have been tested to exquisite precision. Some of the best evidence comes from studies of a pair of rapidly spinning neutron stars and, more recently, from observations of the merging of a pair of black holes. As the pair of neutron stars, or black holes, orbit around each other, Einstein's theory predicts that they should cause ripples in the four-dimensional fabric of space and time (or 'space-time'), which propagate outwards like ripples on a pond.

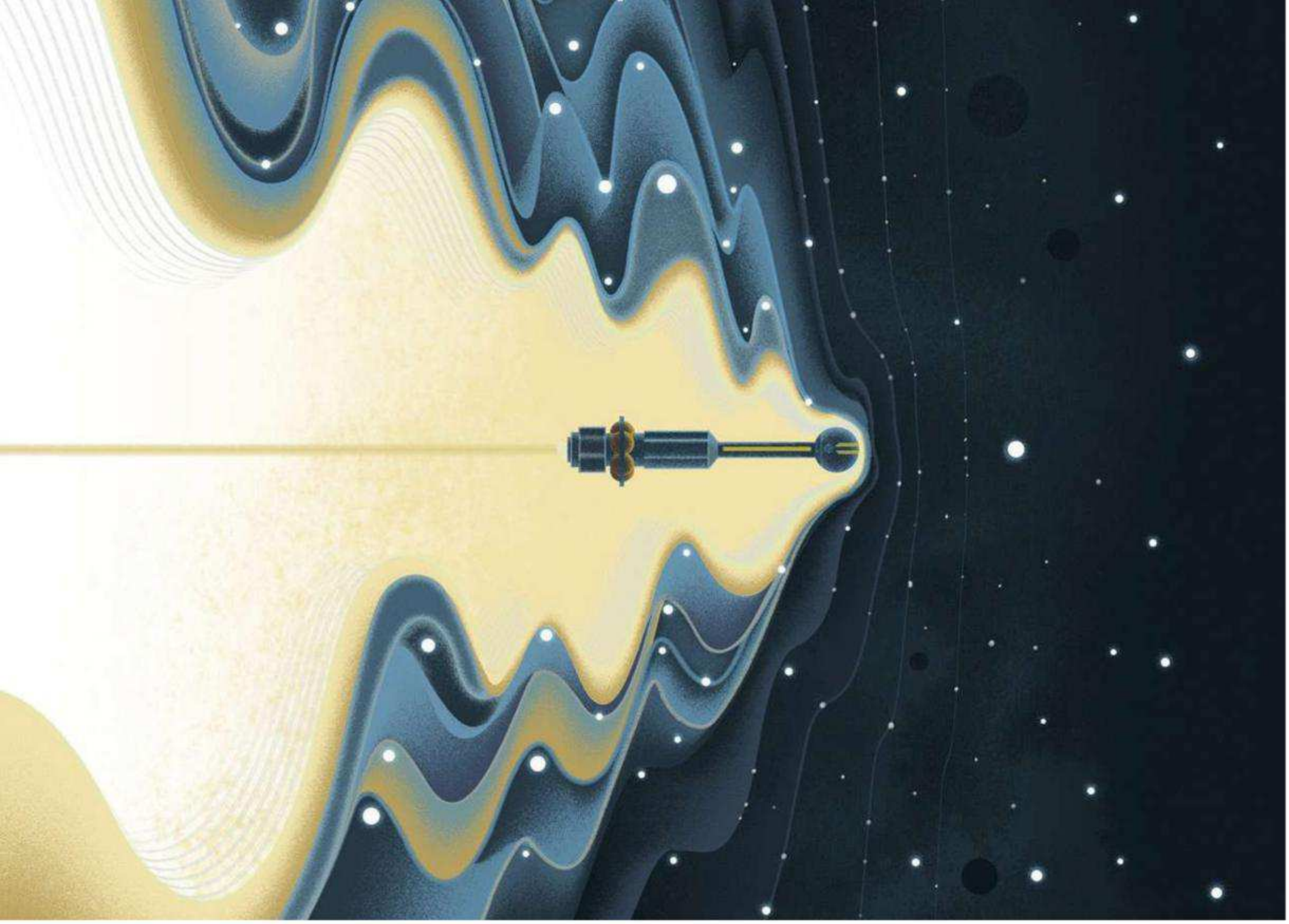


ILLUSTRATION: SAM CHIVERS

# Einstein taught us to ditch our prejudice that space and time are fixed

In the case of neutron stars, the emission of these 'gravitational waves' causes the stars to spiral slowly inward. Astronomers, including those at Jodrell Bank in the UK, have used radio waves emitted by these stars to calculate that they spiral inward at a mere seven millimetres each day. With black holes, the spiralling is more dramatic: they collide, and the predicted ripples in space-time have been directly measured as they pass by our planet. On a more down-to-Earth level, the entire GPS network would fail within hours if the onboard clocks were not adjusted to account for the fact that moving clocks run slow, and that clocks in the weaker gravity of high-Earth orbit run fast (these are opposite effects, but they don't precisely cancel out).

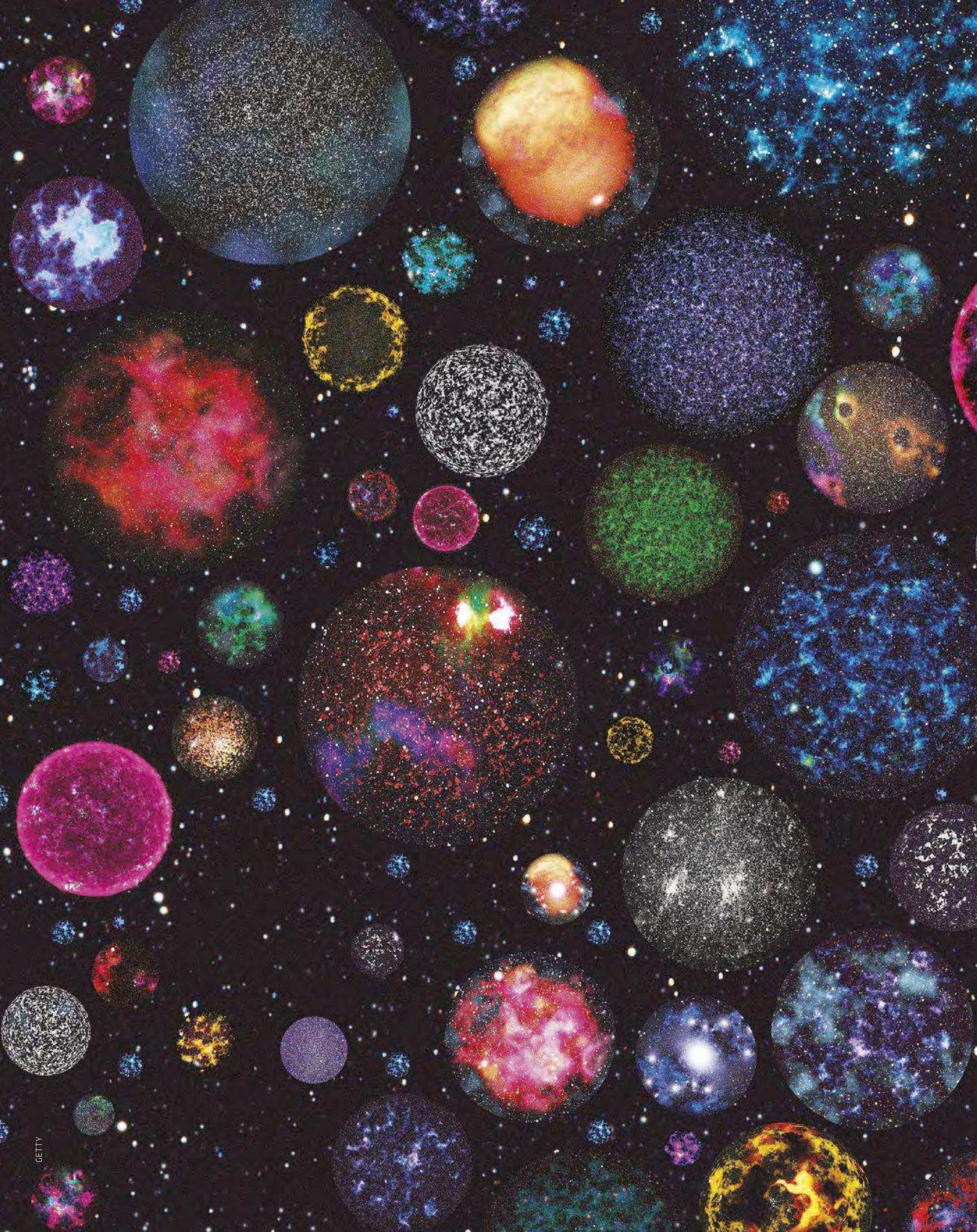
Albert Einstein taught us to ditch our prejudice that space and time are fixed. Instead, we need to see them as malleable and subjective. Together they form a shape-shifting, universal fabric on which the entire cosmos plays out.

BBC FOUR

Watch a clip explaining the concept of space-time *bbc.in/2HPk1r5*

**Jeff Forshaw** is professor of particle physics at the University of Manchester. He has co-authored three popular science books with Brian Cox.

**Brian Cox** is a BBC presenter, and professor of particle physics at the University of Manchester, and the Royal Society professor for public engagement in science.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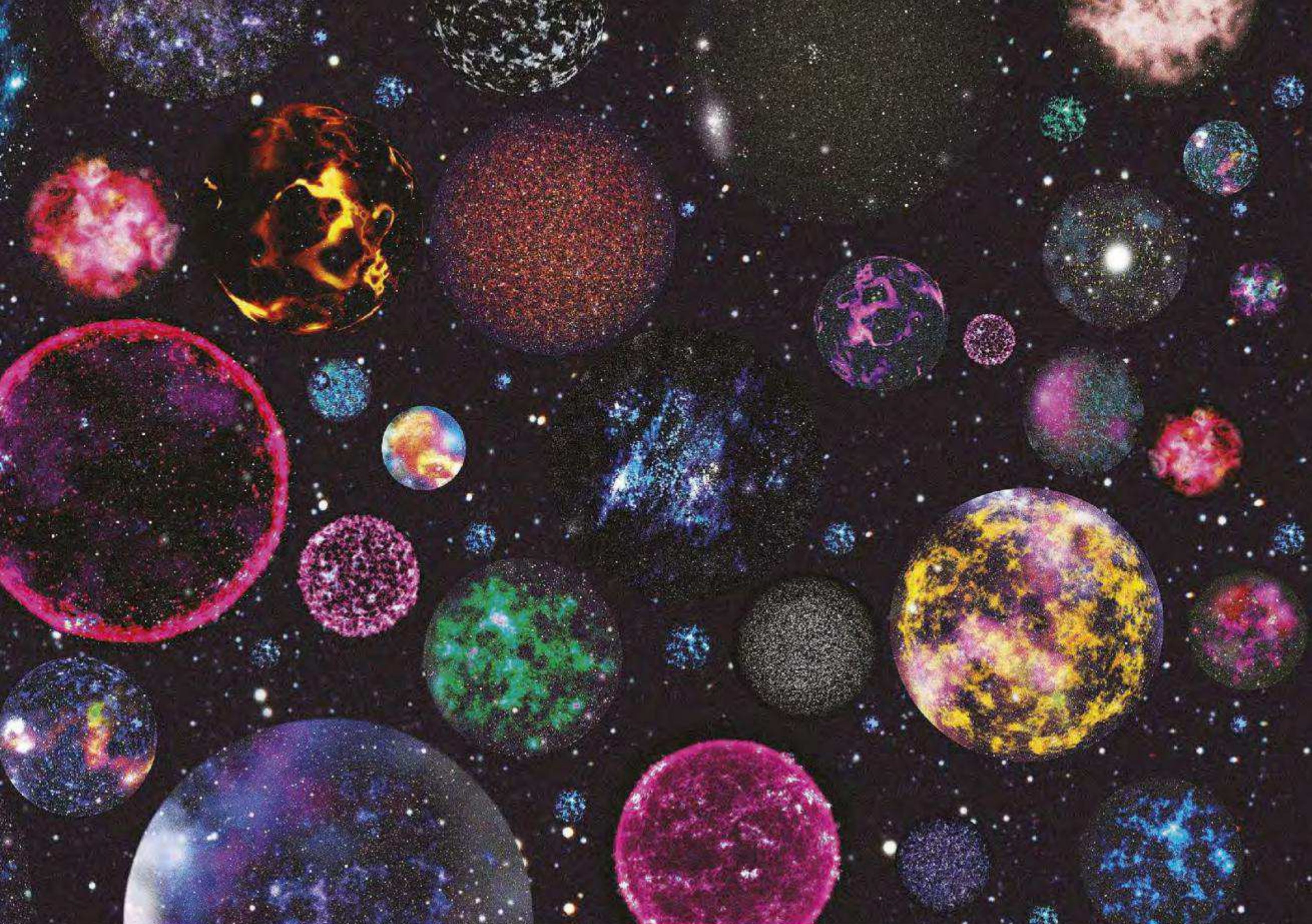


# COSMOLOGY

The immensity of our Universe is mind-boggling, as are many of the strange phenomena lurking in its depths. In this section, we journey through the cosmos, exploring how the Universe came to be, what it might become and the most intriguing anomalies out there.



# BEFORE THE BIG BANG

## The beginning of space, time and everything

WORDS: **JEFF FORSHAW** AND **BRIAN COX**

Probably the most audacious idea in science is that it's possible to track the evolution of the Universe starting from a time, around 13.8 billion years ago, when everything we see today was squeezed into a space far smaller than the size of a proton.

The vastness of the cosmos is hard to appreciate, but take a look at the Sloan Digital Sky Survey on page 49. Each tiny dot in this image is a galaxy, and each galaxy typically consists of hundreds of millions of stars. Our own Sun is one such star, residing in the Milky Way, and the Andromeda galaxy is our nearest neighbour, at a mere 2.5 million light-years away.

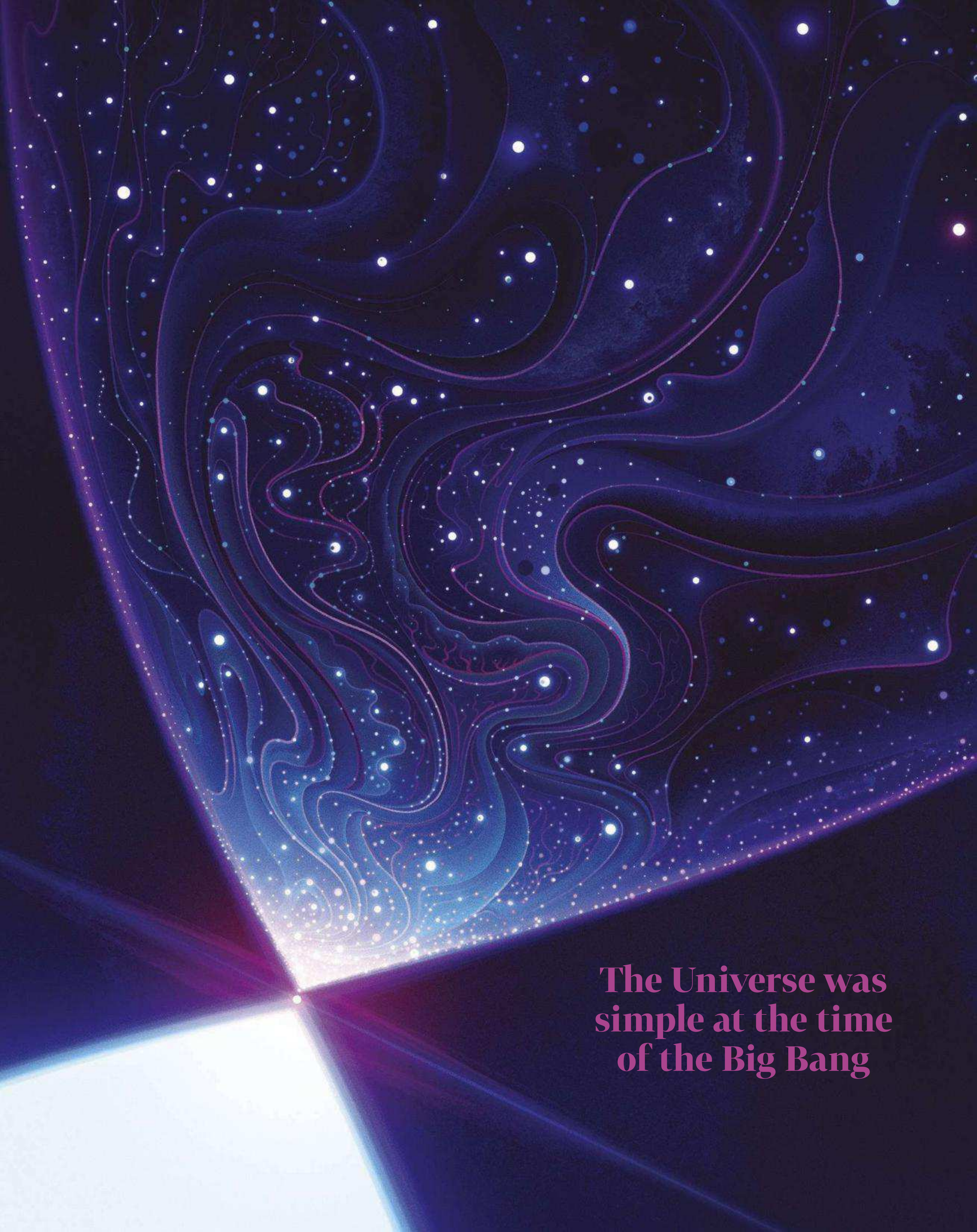
The Sloan Digital Sky Survey is a map created by astronomers. It covers about one-third of the sky – just a small portion of everything that's out there. Apart from being mind-blowing in its scale, the map is also noteworthy for the fact that the galaxies make a wispy pattern, with strands and clumps and voids. And that pattern, which forms the structure of the Universe, can be explained using a theory that may well be the jewel in the crown of modern cosmology.

### AN EVOLVING COSMOS

The Universe wasn't always like it is now. Around 13.8 billion years ago, the Big Bang happened (see 'The key idea', page 48). This is the time when all of the elementary particles that produced the stars and galaxies were first created. The Universe was simple at the time of the Big Bang (it's the present-day Universe that's hard to understand). This is good news, because it means cosmologists can do the calculations to work out how things evolved.

At the time of the Big Bang, the Universe contained a hot, almost featureless gas of elementary particles. That word 'almost' is absolutely crucial here, because the density of particles in the gas wasn't entirely uniform:

ILLUSTRATION: SAM CHIVVERS

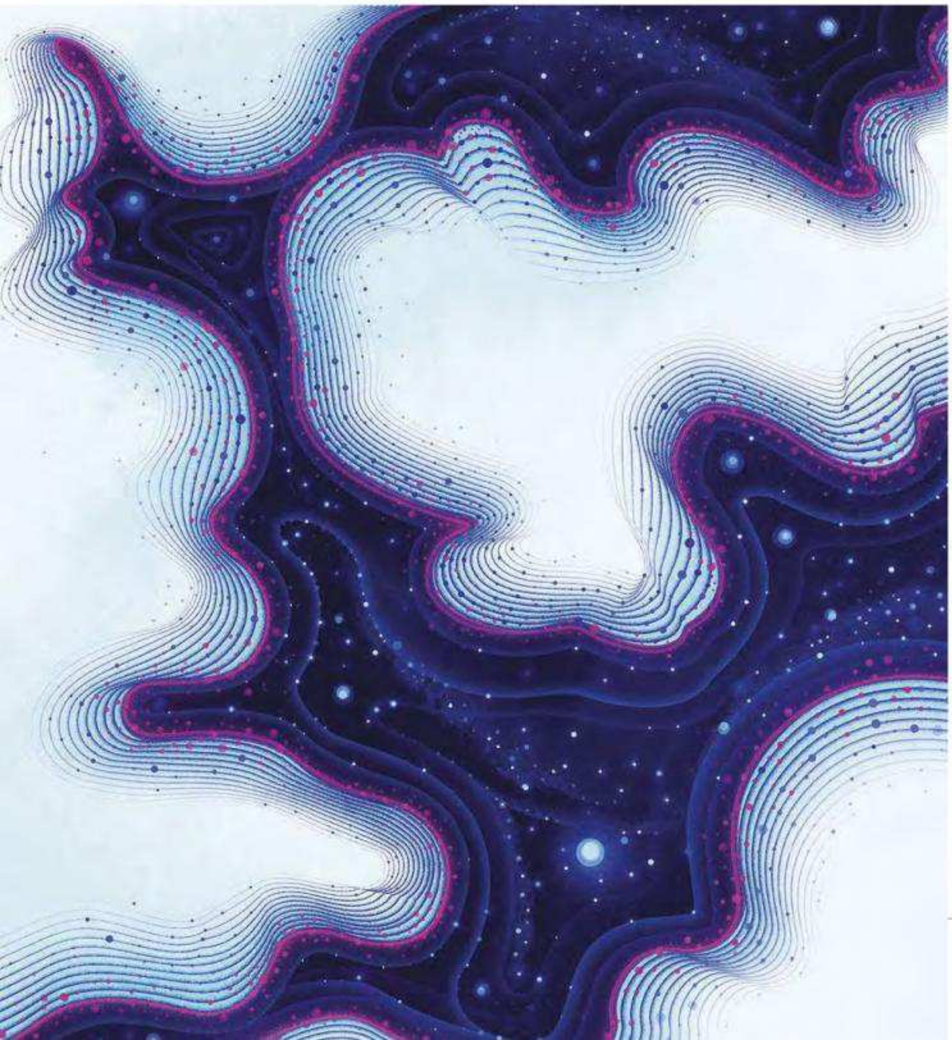


**The Universe was simple at the time of the Big Bang**

THE KEY IDEA

## OUR UNIVERSE IS AN EXPANDING FRUIT CAKE

The Big Bang is like baking a fruit cake. As the cake expands, the pieces of fruit all move away from each other, and so it is with the Universe: space expands and the galaxies move further apart. The idea that space is malleable and can expand may seem a little weird, but it's a consequence of Einstein's Special and General Theories of Relativity. The Big Bang is analogous to the time when the pieces of fruit were very close together, just after the cake was popped into the oven. Today, the cake is still cooking and the expansion of our Universe even appears to be speeding up. One common misconception regarding the Big Bang is that everything expanded away from a point in space. This is wrong. Indeed, it's likely that the Universe was vast, even at the time of the Big Bang. It was vast and of very high density, which means the particles were very close together. Rather like the case of a very large piece of raw dough prior to baking, when the pieces of fruit were very close together.



some regions had a marginally higher density than others. Knowledge of this pattern of density variations is enough for cosmologists to evolve the gas forwards in time.

At first, this gas cooled and expanded but, gradually, gravity caused the higher density regions to draw in more matter and become denser. After a few hundred million years, some clouds of hydrogen became dense enough to ignite and burn via nuclear fusion – these were the first stars. Cosmologists can compute how the stuff of the Universe evolved from a hot, dense gas all the way to the formation of galaxies: the key input to their calculations is knowledge of those original variations in the density of the gas. But, of course, to know those requires some idea of what actually caused the Big Bang in the first place.

### BACKGROUND NOISE

Over the past 15 years or so, cosmologists have become more confident in one theory for the origin of the Big Bang, known as inflation. Inflation is able to predict the pattern of density variations at the time of the Big Bang and this means that we're able to compute the observed pattern of galaxies in our Universe.

As if this weren't amazing enough, there's even more impressive proof for the theory of inflation: it can also predict the details of the cosmic microwave background (CMB). Essentially, this is the cooled, faded afterglow of the Big Bang, which gives us a picture of the Universe when it was just a few hundred thousand years old.

The CMB is light that has been travelling unimpeded across space since it started its journey 380,000 years after the Big Bang. At this point in time, light suddenly stopped interacting with the surrounding gas and headed off in largely uninterrupted straight lines. Today, we can measure this light in the form of microwaves (it started out as infrared light, but has stretched due to the expansion of the Universe). By measuring the CMB cosmologists are able to map the density variations in the cooling gas that existed shortly after the Universe was born (see 'Microwaves arriving at Earth today' on page 51). We can then compare these observations with theoretical

computations. If we suppose that the Big Bang started out with the pattern of density variations predicted by inflation, the computations give the exact CMB that we observe in reality, which is serious evidence in favour of inflation. But what exactly is inflation?

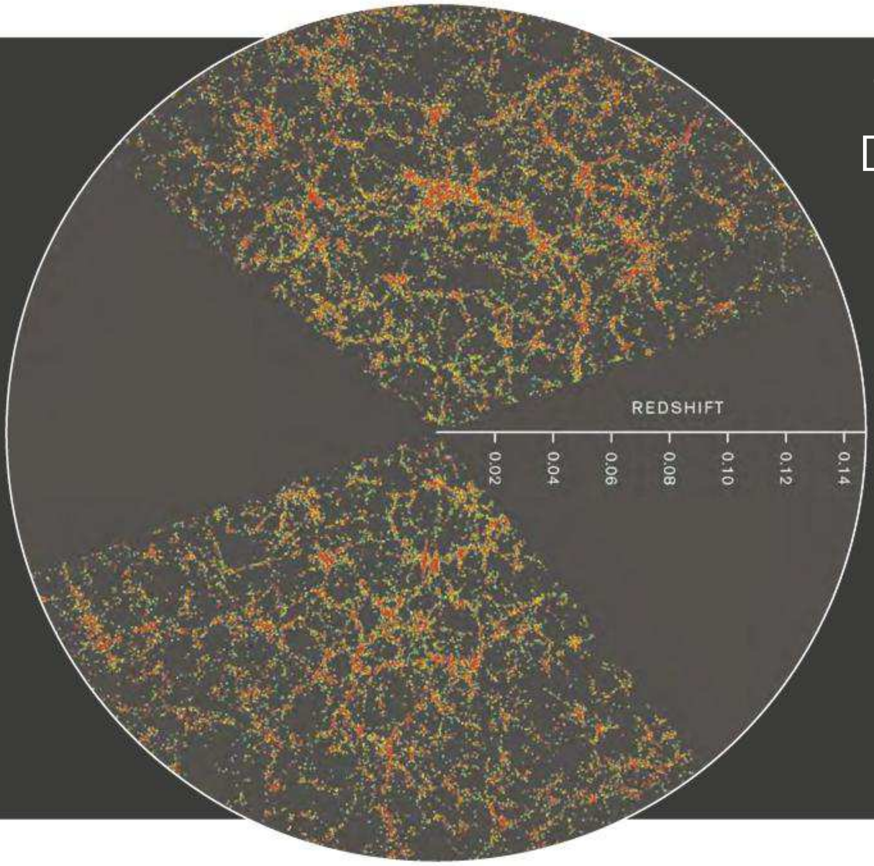
**COSMIC TREACLE**

The theory of inflation emerged in the early 1980s and initially had nothing to do with the distribution of galaxies or the CMB. Instead, it began with the idea that empty space might be filled with an invisible scalar field – a kind of cosmic treacle. This field would permeate all of space, like a still ocean, and ripples in the field would be manifested as particles.

This idea is familiar to particle physicists because one such field is the Higgs field, accompanied by the Higgs boson particle – which was discovered in 2012 (see page 6). Without the Higgs field, elementary particles would have zero mass and would zip around at the speed of light, so atoms wouldn't form.

The existence of the Higgs field also means that there should be an energy associated

## In around 100 billion years, the Milky Way will be part of a single supercluster of galaxies




## THE SLOAN DIGITAL SKY SURVEY

A map of the Universe from the Sloan Digital Sky Survey. Each dot represents a galaxy and the red regions have a higher density of galaxies. The Milky Way is at the centre and the redshift value indicates how far away the galaxies are (the most distant are almost two billion light-years away).

## JARGON BUSTER

**BIG BANG**
This is the time when the Universe was densely populated with elementary particles moving around in a very hot gas. It occurred 13.8 billion years ago.

**BUBBLE UNIVERSE**
This is a region of the Multiverse in which inflation has halted, giving rise to a Big Bang. Our visible Universe could be such a region.

**COSMIC MICROWAVE BACKGROUND**
These are photons that have been travelling in straight lines across the vastness of space since a time 380,000 years after the Big Bang.

**INFLATION**
This was the time before the Big Bang when space underwent an ultra-rapid expansion.

**INFLATON**
This field pervaded space and caused inflation to occur. The decay of the inflaton is what generated the particles of the Big Bang.

**MULTIVERSE**
In some theories of inflation, the entire Universe is called the Multiverse and it contains a large number of bubble universes. Each bubble universe is separated from the others by a vast, rapidly expanding space.

**VISIBLE UNIVERSE**
This portion of the Universe includes stars, galaxies and everything that we can see. The Universe is bigger than this: we can't see everything because the light from the most distant objects hasn't yet reached us.

with what we think of as empty space and this energy can act as a source of dark energy. This dark energy would cause space to accelerate in its expansion. The trouble is that current theories in particle physics seem to suggest that this accelerated expansion should be far faster than astronomers observe. The fact that, today, the amount of dark energy is much less than expected is one of the biggest mysteries in particle physics.

Nevertheless, the possibility that other, similar fields might exist led cosmologists to consider that the Universe might have undergone a period of ultra-rapid expansion in its past. The remarkable thing is that this idea turns out not only to be feasible, but also offers an explanation for the origin of the Big Bang itself.

> **The fact that, today, space is slightly accelerating implies the Universe will never end**

**NEW BEGINNINGS**

The basic idea of inflation is that empty space was once filled with an inflaton field, and that the energy stored in this field caused the space to rapidly expand. This expansion was most likely so rapid that, before long, the Universe was a cold and empty place as everything rushed away from everything else. After a time, this rapid expansion drew to a close as the energy stored in the inflaton field drained away, leaving behind a Universe filled with a cold gas of inflaton particles. These inflaton particles then decayed into other, more stable, particles and, in doing so, they generated the Big Bang, as the energy locked away in the cold gas of heavy inflaton particles got converted into a hot gas of lighter particles.

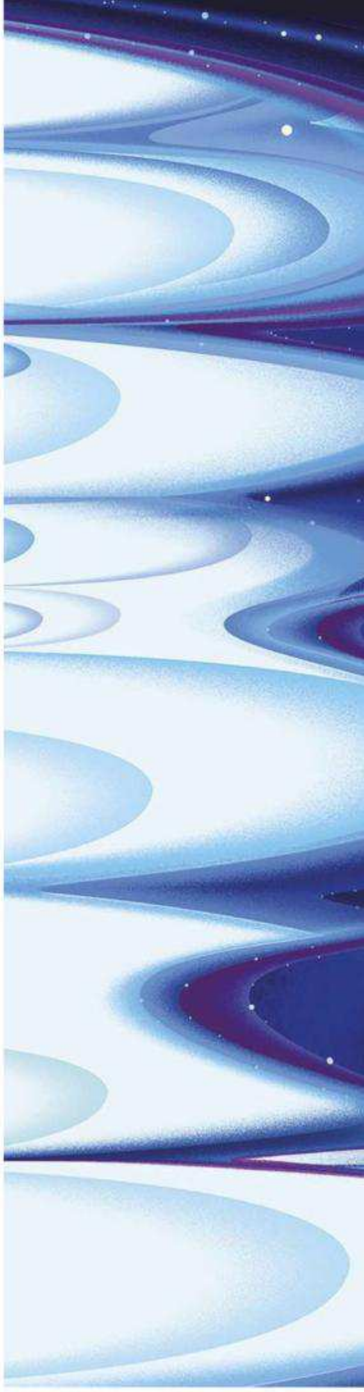
The idea of inflation was attractive to cosmologists because it generates a big Universe (due to that early phase of rapid expansion). But it wasn't long until they realised that the theory had more to offer: it also predicts the pattern of density variations at the time of the Big Bang. In other words, it offers a detailed description of how matter was spread about at the time of the Big Bang, and this (as previously mentioned) is in precise accord with the patterns seen in the observed galaxies and cosmic microwaves.

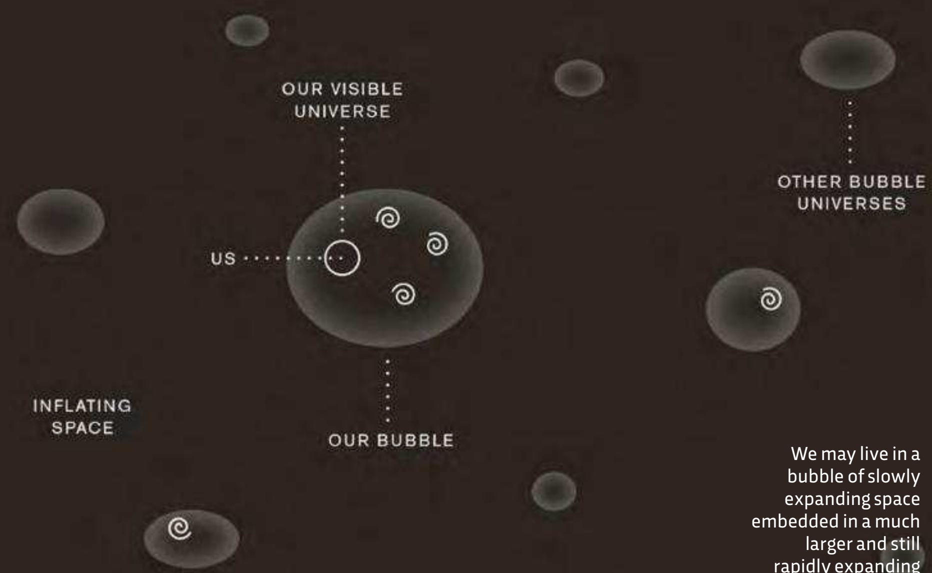
This stunning success of inflation arises as an unavoidable consequence of quantum physics. The mathematics allows us to consider going back to a time, just before the Big Bang, when the portion of space that was destined to grow into the entire visible Universe was less than a billion times smaller than a single proton. This is utterly mind-boggling but there appears to be no impediment to calculating what happened at this time.

Crucially, the inflaton field wasn't a perfectly still ocean – it was rippled. These ripples were generated as a consequence of Heisenberg's Uncertainty Principle, a key result in the theory of quantum physics (see page 22). Heisenberg's principle tells us that nothing can ever be entirely still – even empty space is fizzing with particles that appear and disappear from nowhere. So, the inflaton field must have had ripples, and these were translated into corresponding ripples in the density of matter at the time of the Big Bang. How wonderful that this extraordinary science is writ large on the sky and that we are so fortunate to be here to decode the message.

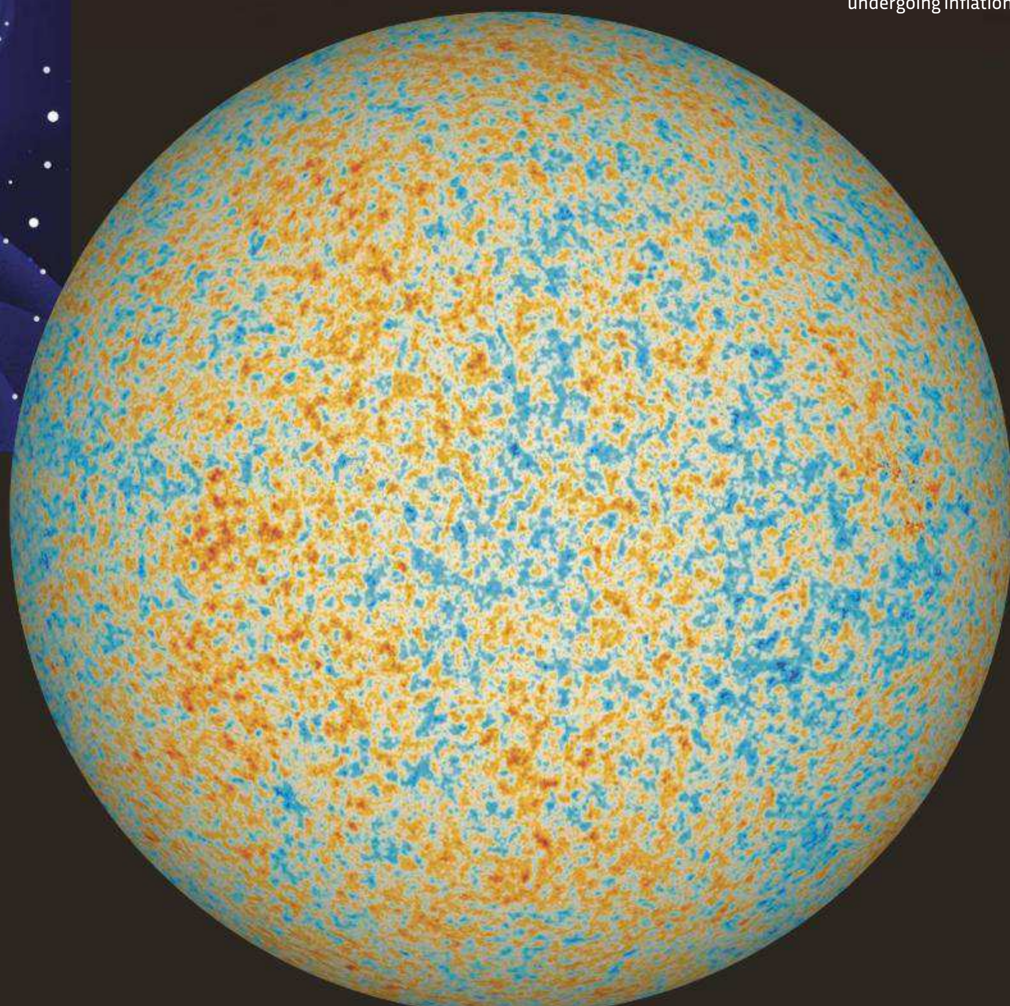
With inflation, we now have an explanation for the origin of the Big Bang and a new way of thinking about how our part of the cosmos came to be. It could even be that inflation was occurring for a very long (possibly infinite) period of time before it halted in the region of space destined to grow into the Universe we see around us. In that case, the Big Bang was not the beginning. Rather it was just a moment in the history of the Universe.

Looking to the distant future, the fact that, today, space is slightly accelerating in its expansion implies that the Universe will never end. It'll continue to expand forever, becoming ever more dilute and cold. In around 100 billion years, the Milky Way will be part of a single supercluster of galaxies, and all





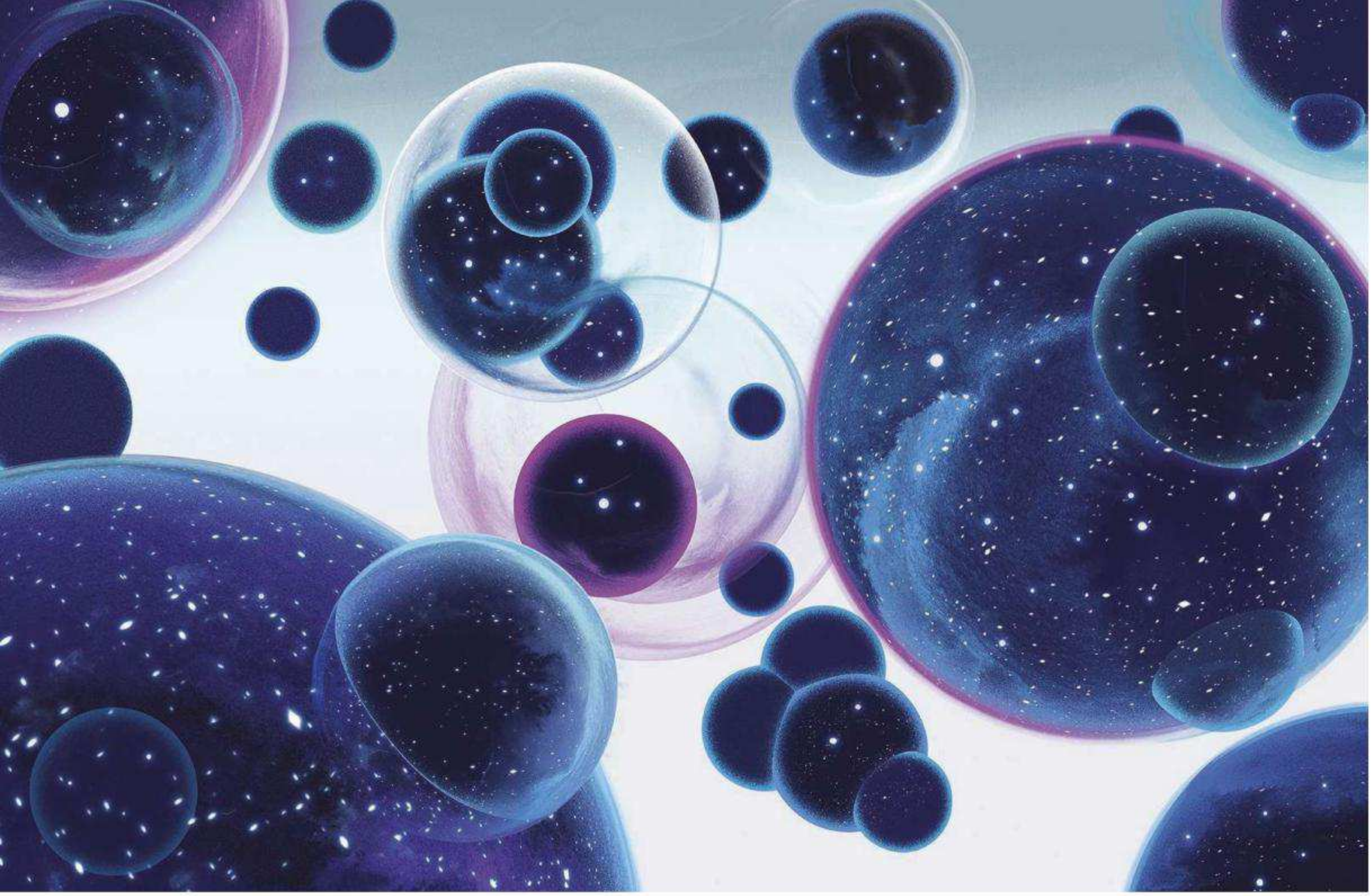

We may live in a bubble of slowly expanding space embedded in a much larger and still rapidly expanding space that's undergoing inflation



## MICROWAVES ARRIVING AT EARTH TODAY

**Pictured right is an image of the microwaves that bathe the Earth today, as measured by the Planck satellite, a space telescope operated by the European Space Agency between 2009 and 2013. The colours represent the temperature of the microwaves hitting our planet, which vary by only approximately 100-millionths of a degree. These tiny temperature variations are directly related to the density variations in the gas that existed 380,000 years after the Big Bang.**

NASA ILLUSTRATION: SAM CHIVVERS



**We are privileged to be living in an epoch when we're able to learn so much about the wonders of the cosmos**

other galaxies will be racing away at such a speed that light from them could never reach the Earth. This means that astronomers of the far future would have no distant galaxies to observe – to them, the Universe would seem a much duller place than we know it to be. We are privileged to be living in an epoch when we're able to learn so much about the wonders of the cosmos and its origins.

There's a final, mind-boggling twist to the story of inflation. We've just said that inflation might have been occurring forever before the Big Bang. It's also possible that inflation didn't stop everywhere in the Universe at the time of the Big Bang. We may be living in a bubble of slowly expanding space embedded in a much larger and still rapidly expanding space that's undergoing inflation. There may even be other bubble universes like ours, rushing away from us at an unimaginable speed. According to some theories, it's conceivable that the laws of physics are different in each of these bubble universes. In other words, every variant on nature's laws is played out somewhere in the vastness of this Multiverse (see page 76). Now there's a thought.

BBC RADIO 4

Listen to *A History of Ideas* for more on the Big Bang *bbc.in/2HpSjSm*

**Jeff Forshaw** is professor of particle physics at the University of Manchester. He has co-authored three popular science books with Brian Cox.

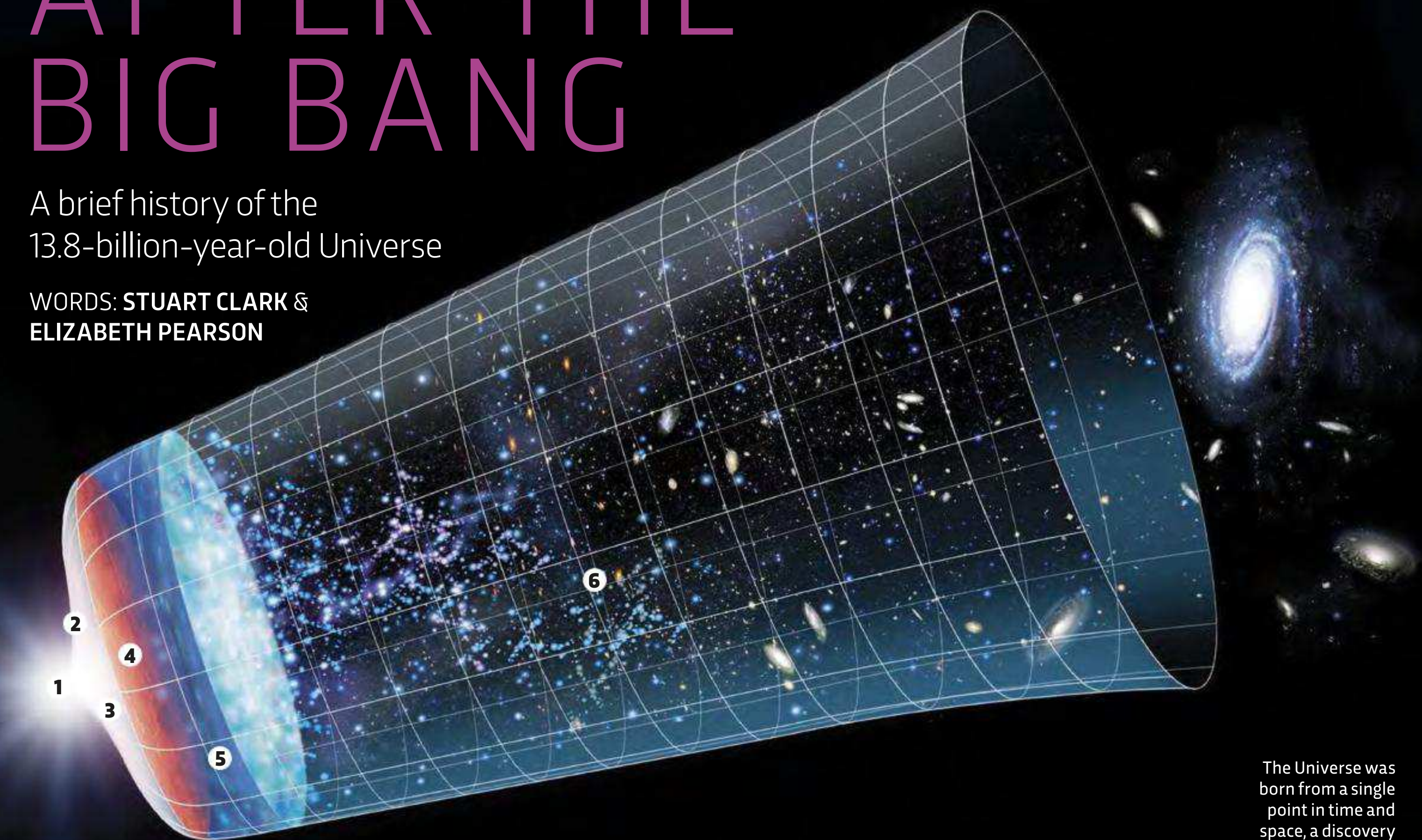
**Brian Cox** is a presenter, a professor of particle physics at the University of Manchester and Royal Society professor for public engagement in science.

ILLUSTRATION: SAM CHIVVERS

# AFTER THE BIG BANG

A brief history of the 13.8-billion-year-old Universe

WORDS: **STUART CLARK & ELIZABETH PEARSON**




The Universe was born from a single point in time and space, a discovery made possible by identifying the radiation from the Big Bang itself

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## ❶ THE BIG BANG

At the moment of the Big Bang, 13.8 billion years ago, there were no stars or galaxies, just a hot, dense sea of particles and radiation. Straight after the Big Bang, space began to expand, spreading out the matter and energy.

## ❷ INFLATION

10-35 SECONDS POST-BIG BANG

In the blink of an eye, the Universe grew bigger by a factor of at least 1,060.

## ❸ PARTICLE CREATION

1 MINUTE POST-BIG BANG

At one minute old, the entire Universe resembled the interior of a star on a vast scale. Particles that would become the nuclei of all the atoms in the Universe were built in this cauldron. Mostly these were single protons that would become hydrogen, but around a quarter of the particles transformed into helium nuclei. Trace amounts of lithium and beryllium were also produced.

## ❹ THE DECOUPLING OF MATTER AND ENERGY

380,000 YEARS POST-BIG BANG

Until this moment it had been impossible for whole atoms to form; whenever a nucleus and an electron particle bonded together, the radiation smashed them apart again. Now, the continual expansion of space had weakened the radiation so much that it could no longer break apart the atoms. The afterglow of the radiation was captured by the Planck satellite (see page 51).

## ❺ THE COSMIC DARK AGES

1 MILLION YEARS POST-BIG BANG

The expansion of space stretched the radiation into the infrared and then into the microwave sections of the electromagnetic spectrum. The Universe became dark. There were no stars, so no sources of light. Slowly, the sea of atoms began to fragment into clumps, pulling together to become the first celestial objects. The first stars were purely hydrogen and helium. They lived for just hundreds of thousands of years before destroying themselves and seeding the Universe with the heavier elements needed to form planets and life.

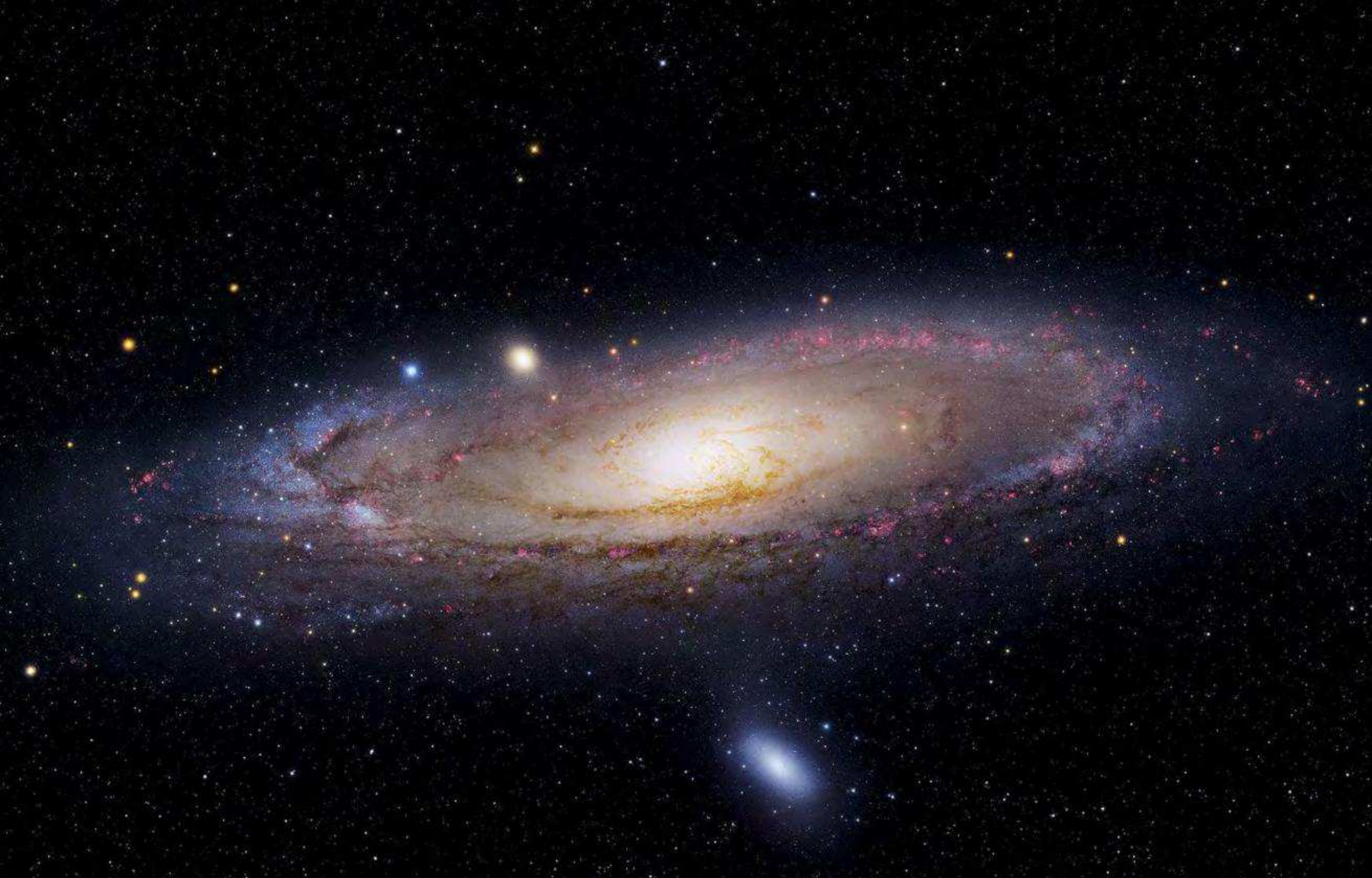
## ❻ THE FORMATION OF THE SOLAR SYSTEM

8.8 BILLION YEARS POST-BIG BANG

The Solar System started out as a huge cloud of gas (hydrogen and helium), which collapsed and fused together until it formed the star that we now know as the Sun. Before our star was born, another larger one had died in a supernova, filling the cloud with gas and dust. This debris gradually formed a protoplanetary disc – a huge, flat ring comprising hundreds of lumps of rock and ice known as planetesimals, which were the building blocks of the Solar System. After a few million years of crashing and melding together, these bodies began to resemble the planets as we know them today.


**Stuart Clark** is an author, cosmology consultant for the European Space Agency and a Fellow of the Royal Astronomical Society.

**Elizabeth Pearson** is the staff writer on *BBC Sky at Night* magazine.



# The end of the Universe

IF THE UNIVERSE DOES END, WILL IT DO SO IN A BANG OR A WHIMPER?

WORDS: **BRIAN CLEGG**

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Let's start with what we do know. The Universe we can see originated around 13.8 billion years ago, beginning to expand with the Big Bang. The details of how this occurred and what, if anything, existed before it are speculative (see page 46). The same is true of how the Universe will end – if indeed it does end. But we can speculate – and there are four scenarios that have the most support…

### HOW MIGHT THE UNIVERSE END?

Of the four favoured scenarios, two involve the Universe continuing to expand, continuously getting thinner and more dispersed, although the final outcomes are very different. The most conventional, the Big Freeze, is simply the ultimate outcome of standard thermodynamics. Everything evens out until there is simply nothing happening in a totally diffuse Universe. The more dramatic version takes into account the observation that the Universe is not just expanding, but that the expansion is accelerating. If this accelerating expansion is extrapolated to the extreme, we get the Big Rip, in which all of the matter in the Universe, from planets and galaxies to fundamental particles and space-time itself, is pulled apart as the expansion heads off to infinity.

**It's a bit like trying to predict the stock market. There are clear trends, but it's possible that we'll get caught out in a crash**

By contrast, the other two scenarios see the expansion of the Universe eventually reversing. If everything ends in the Big Crunch, we see a reversal of everything we've experienced to date, returning to an infinitely dense point – a 'singularity'. This can then produce a new Big Bang and a new Universe, giving a possibility for a cycle of universes. In the subtly different Big Bounce, the Universe again reaches a peak size and begins to contract, but, in this instance, it never gets as far as a singularity before bouncing and expanding again. The difference from the Big Crunch is that some aspects of the earlier Universe can carry over into the next one. In effect, the Big Crunch generates a new Universe, whereas the Big Bounce sees the same Universe repeatedly expand and contract.

### WHAT DOES IT DEPEND ON?

All these possibilities are devised by taking the observed behaviour of the Universe and then extrapolating some key aspects of physics into the future, notably the General Theory of Relativity. Of all the factors involved in predicting the future of our Universe, the existence of the accelerating expansion is the most reliable. First discovered in 1998, we now even have a figure for the rate of expansion: 73.2 kilometres per second per megaparsec (a megaparsec equals 3.26 million light-years).

The 'extrapolation into the future' part is trickier. We can't experiment with a Universe and try out different scenarios. We only know what has happened so far. There's nothing to say that things will continue in the future the way they have in the past – it's just an assumption. It's a bit like trying to predict the stock market. On the whole there are clear trends, but it's always possible that we'll get caught out in a crash. Perhaps most doubtful is the use of General Relativity. Although Einstein's theory has proved hugely effective

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In the Big Rip scenario, particles tear themselves apart, and space-time could disintegrate

## JARGON BUSTER

**BRANE**
Some theories combining quantum physics and gravity require there to be at least 10 dimensions. In such scenarios, objects with fewer dimensions called branes (short for membranes) could float in the multidimensional environment.

**COSMOLOGY**
The branch of astronomy concerned with the origin, evolution, and eventual fate of the Universe.

**SINGULARITY**
Various physical models predict that certain characteristics of cosmic objects – their density, for example – will get bigger and bigger until they become infinite. When this happens, it's called a singularity and current theory breaks down.

# HOW COULD OUR UNIVERSE END?

There are four popular scenarios...

## BIG BOUNCE

As the shrinking Universe approaches the singularity, quantum effects cause the subatomic particles that permeate the cosmos to repel each other. The collapse reverses and the same Universe begins to expand again.

## BIG RIP

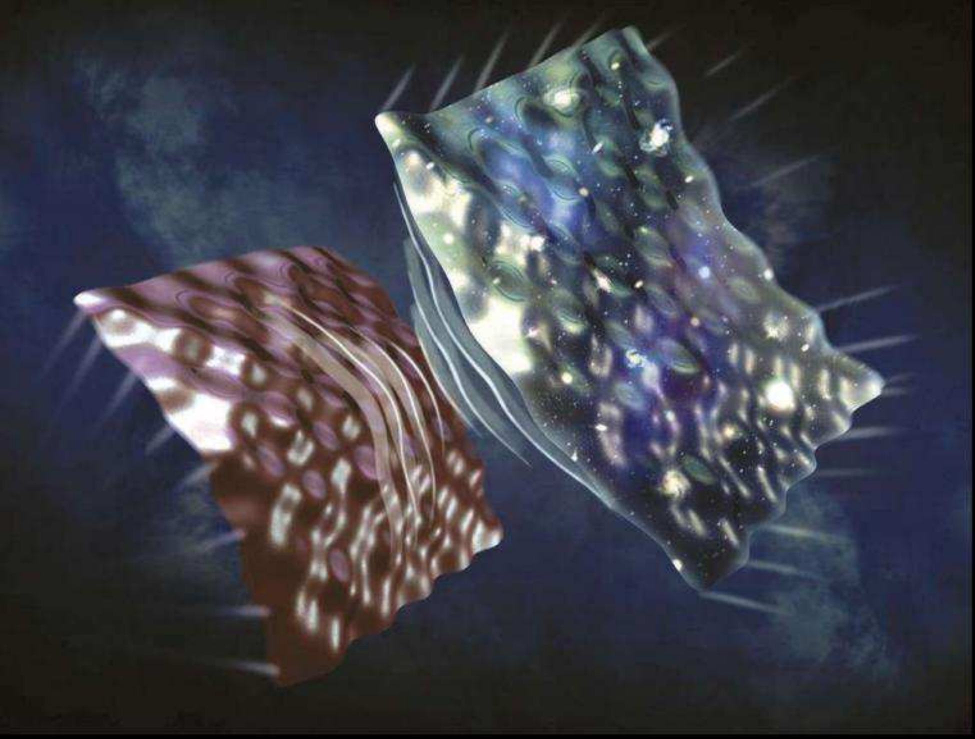
With an ever-accelerating expansion, everything in the Universe (including fundamental particles) rip themselves apart, giving off vast amounts of light. In the extreme, space-time itself disintegrates.


## BIG FREEZE

The Universe cools and runs out of energy as it expands. Matter particles drift aimlessly through space and star formation ceases, plunging the cosmos into a frigid darkness.

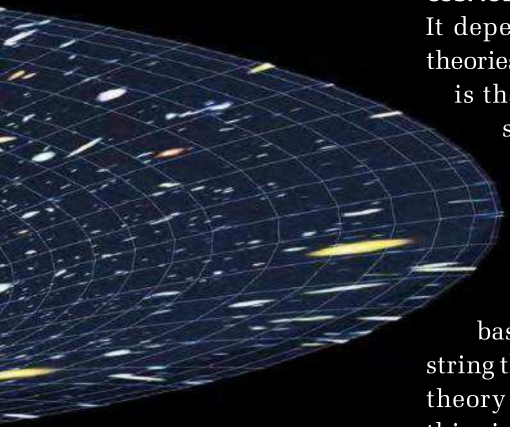
## BIG CRUNCH

The expansion reverses and the Universe shrinks down to an infinitely dense point – a singularity – where all physics as we know it breaks down, triggering a new big bang.



## Based on this, our Universe has at least 20 billion years to go, but this is very speculative

In the Big Bounce scenario, subatomic particles repel each other



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in predicting the effects of gravity, it doesn't work at the level of quantum particles – the physics required in most end-of-the-Universe scenarios. Also, using the theory to model the Universe requires vast simplifications, making the model significantly different from reality.

### WHICH THEORY IS THE MOST POPULAR AMONG COSMOLOGISTS TODAY?

It depends who you ask! The problem with theories like the Big Crunch and the Big Bounce is that models of the Universe suggest that such processes would run out of steam, unable to keep recycling unless there was some external input.

The best supported version of the Big Bounce depends on something called 'ekpyrotic theory', a concept based on an unproven advanced version of string theory – an attempt to combine quantum theory and General Relativity. According to this picture, our Universe is a four-dimensional 'brane' (three of space, one of time), floating in a space-time continuum, and the Big Bounce occurs when two such branes collide, providing that external input.

Variants of the Big Freeze, or 'heat death', in which everything runs out of energy and stars finally stop forming in around 100 billion billion years, were most popular among cosmologists for a long time. Now, though, the Big Rip is probably the best supported theory, because dark energy – the entity that's speeding up the expansion of the cosmos – seems to be driven by the size of the Universe, so the bigger it gets, the more powerful the effect. It's an eternal feedback loop. Based on this, our Universe has at least 20 billion years to go, but this is very speculative – we don't know, for instance, if dark energy will continue to have the same effect.

### COULD ANYTHING SURVIVE THE END OF THE UNIVERSE?

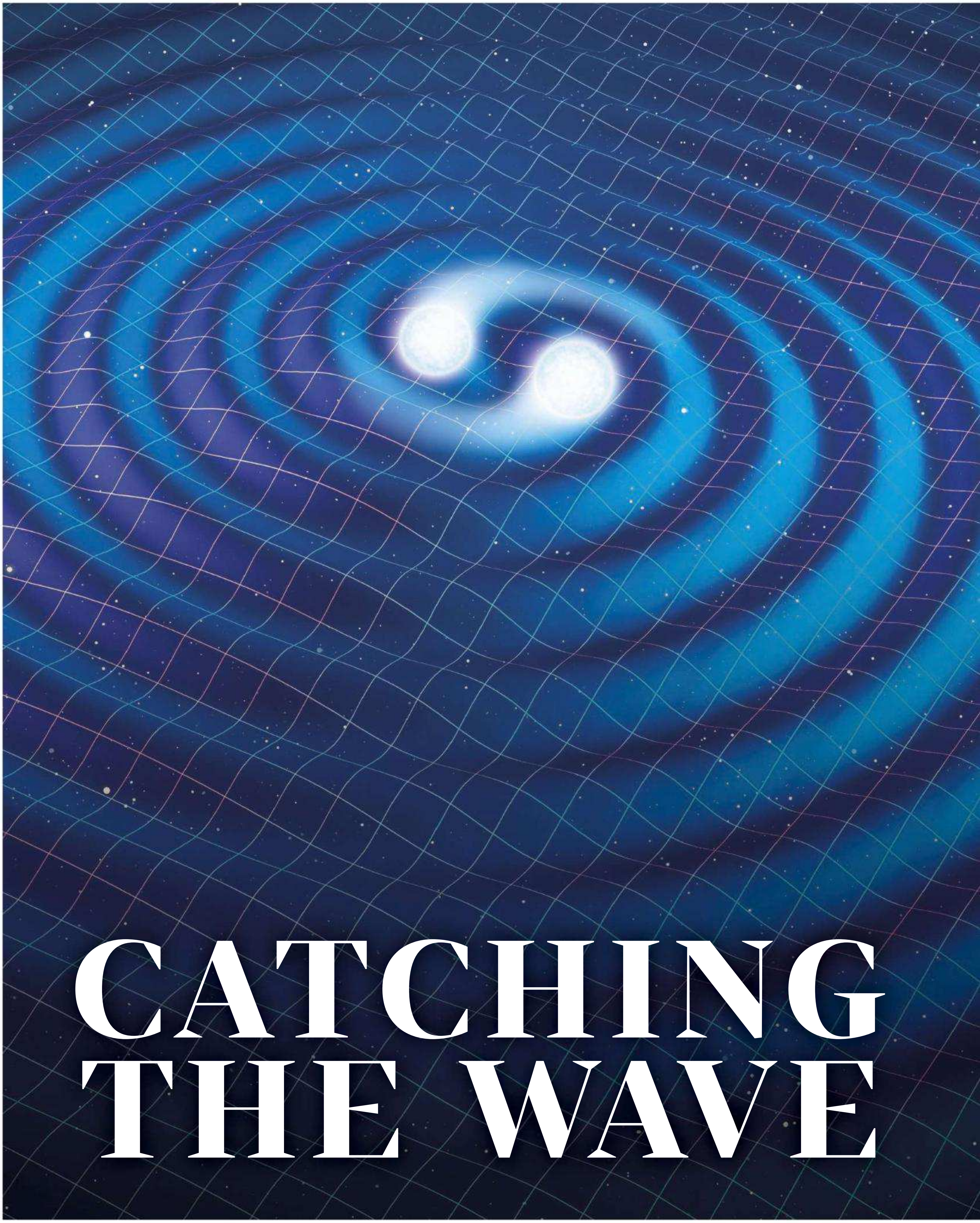
In the favoured scenarios where everything either runs down or splits apart, it's hard to see how this would be possible. But, in a bounce, in principle something could survive – although it it is more likely to be fundamental properties such as the laws of nature than anything with structure like a living being.

### WILL ANOTHER UNIVERSE BE BORN AFTER OURS DIES?

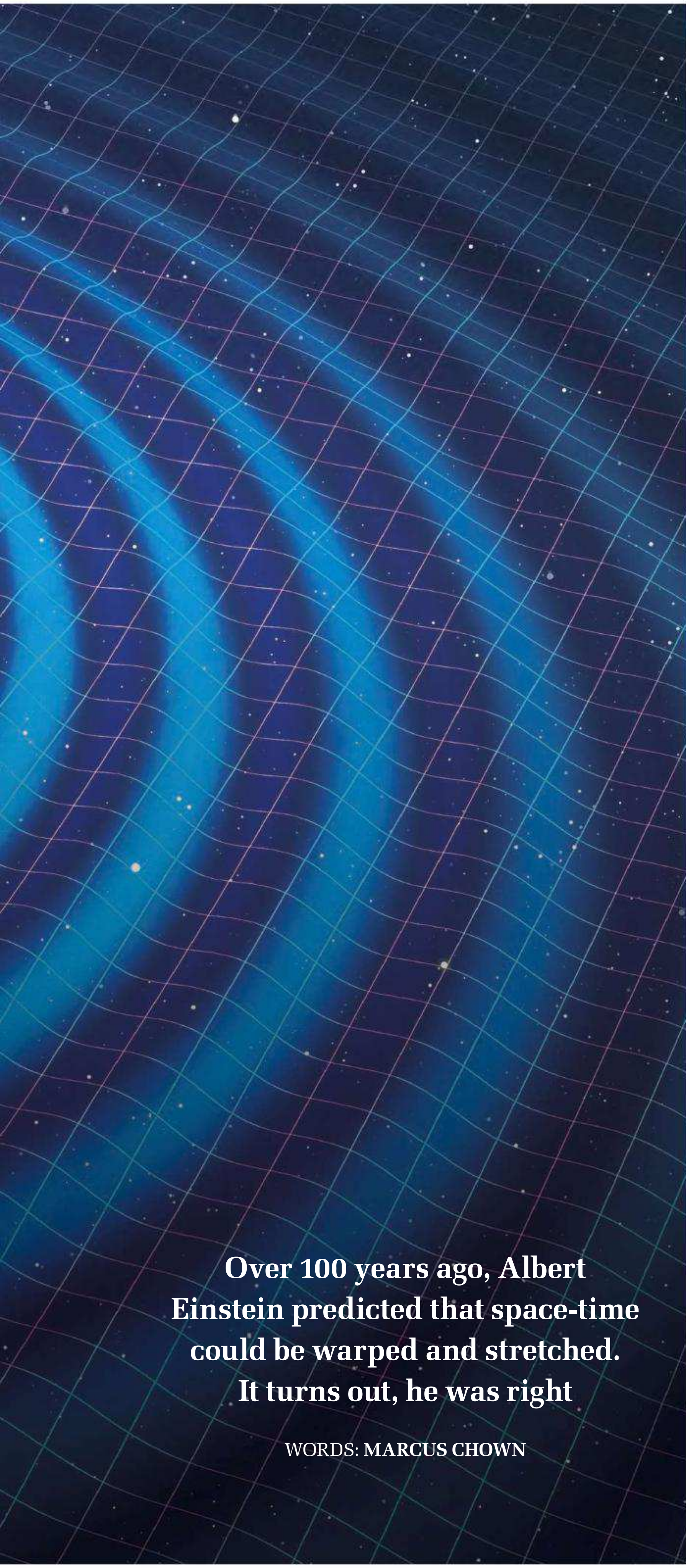
If either the Big Crunch or Big Bounce happens, then yes, definitely. However, even the more likely ever-expanding options don't mean the end of everything.

Most cosmologists believe that our Universe is one of many in a larger Multiverse (see page 76), with big bangs happening regularly. So even if our Universe comes to an end, the larger Multiverse would carry on forever. It's the universal circle of life.

**Brian Clegg** is a science writer. His most recent book is *Gravitational Waves: How Einstein's spacetime ripples reveal the secrets of the Universe*.



# CATCHING THE WAVE



**Over 100 years ago, Albert Einstein predicted that space-time could be warped and stretched. It turns out, he was right**

WORDS: **MARCUS CHOWN**

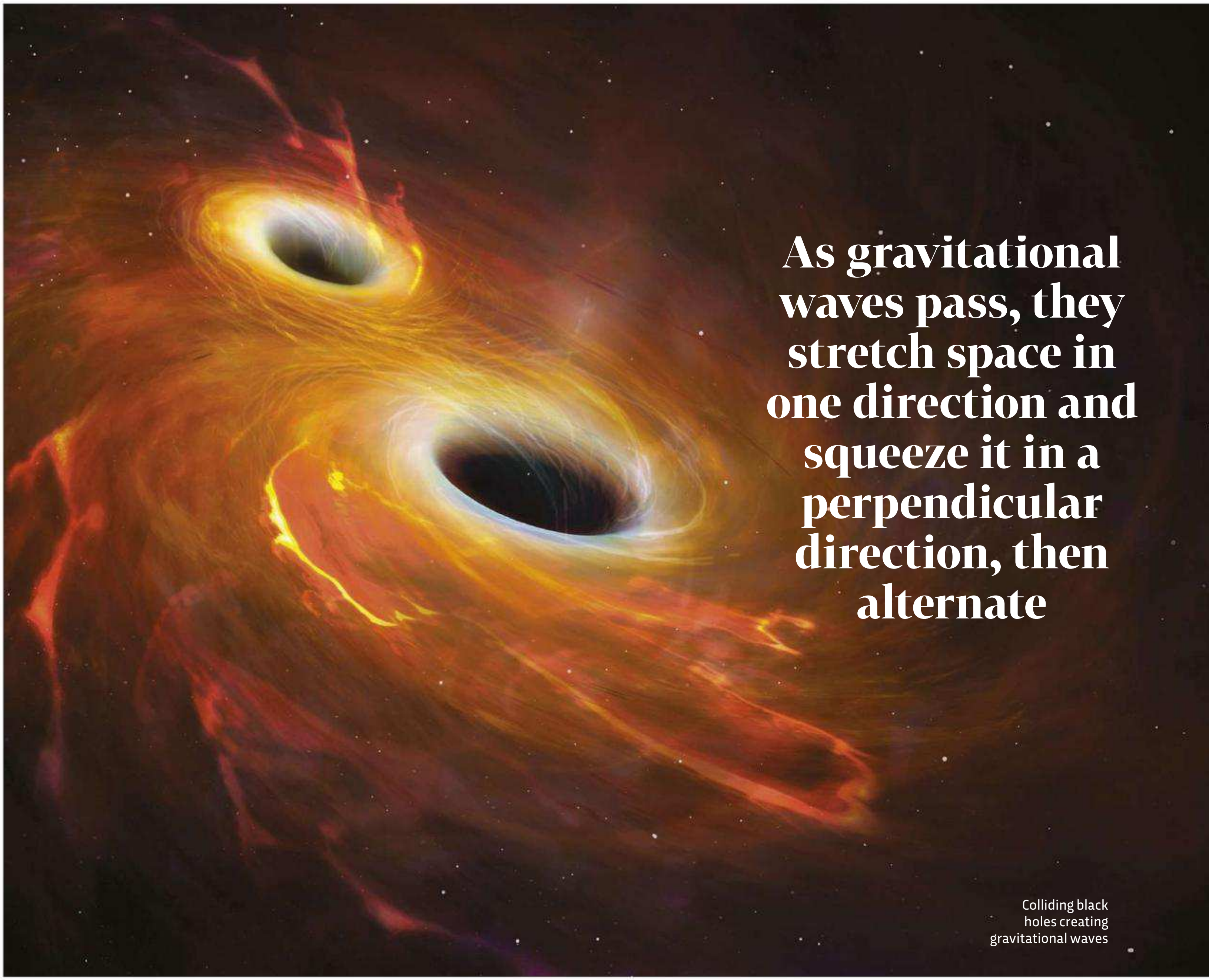
GETTY

Gravitational waves are ripples in the fabric of space-time. They were predicted to exist by Albert Einstein in 1916, although he then got cold feet and retracted his prediction the following year, only to re-make it in 1936.

Specifically, gravitational waves are a prediction of Einstein's General Theory of Relativity. As we found out on page 30, while Isaac Newton had maintained that there was a 'force' of gravity between the Sun and Earth, like a piece of invisible elastic tethering the Earth to the Sun and keeping it forever in orbit, Einstein showed that this is an illusion. No such force exists. Instead, the Sun creates a 'valley' in the space-time around it, and the Earth travels around the edge of the valley rather like a roulette ball in a roulette wheel.

We cannot see the landscape of space-time because space-time – a seamless amalgam of three space dimensions and one of time – is a four-dimensional thing, and we are mere three-dimensional creatures. That is why it took a genius like Einstein to realise that what we think of as matter moving under the influence of the force of gravity is in fact matter moving through warped space-time. As the American physicist John Wheeler said: "Matter tells space-time how to warp and warped space-time tells matter how to move."

According to General Relativity, space-time is no mere passive backdrop to the events of the Universe. Instead it is a 'thing', which can be bent and stretched and warped by the presence of matter. And, if it can be distorted in this way, argued Einstein, it can also be jiggled. When this happens, an undulation of space-time spreads outwards at the speed of light like concentric ripples on a pond: a gravitational wave.



**As gravitational waves pass, they stretch space in one direction and squeeze it in a perpendicular direction, then alternate**

Colliding black holes creating gravitational waves

# HOW ARE GRAVITATIONAL WAVES MADE?

Wave your hand in the air. You just created gravitational waves. Already, they are rippling outwards through space-time. They have left the Earth. They have passed the Moon. In fact, they are well on their way to Mars. In about four years' time they will reach the nearest star system. We already know that one of the three stars of Alpha Centauri is circled by a planet. If it hosts a technological civilisation that has built a gravitational wave detector, at the beginning of 2022, it will be able to pick up the gravitational waves you created by waving your hand a moment ago!

Mind you, the detector will have to be super-sensitive, because gravitational waves (produced whenever mass changes its velocity, or 'accelerates') are extremely weak. The reason for this is that gravity itself is extremely weak. An equivalent statement is that space-time is extremely stiff. Imagine banging a drum. Now imagine replacing the drum skin with something a billion billion times stiffer than steel. That's the stiffness of space-time. This extreme stiffness means that only the most violent movements, such as the merging of super-dense bodies like neutron stars and black holes, can create appreciable gravitational waves.

**1.3 billion**

The number of years the gravitational waves detected on 14 September 2015 had been travelling across space to Earth.

GETTY, LIGO/CALTECH/MIT

# HOW ARE GRAVITATIONAL WAVES DETECTED?

**44**

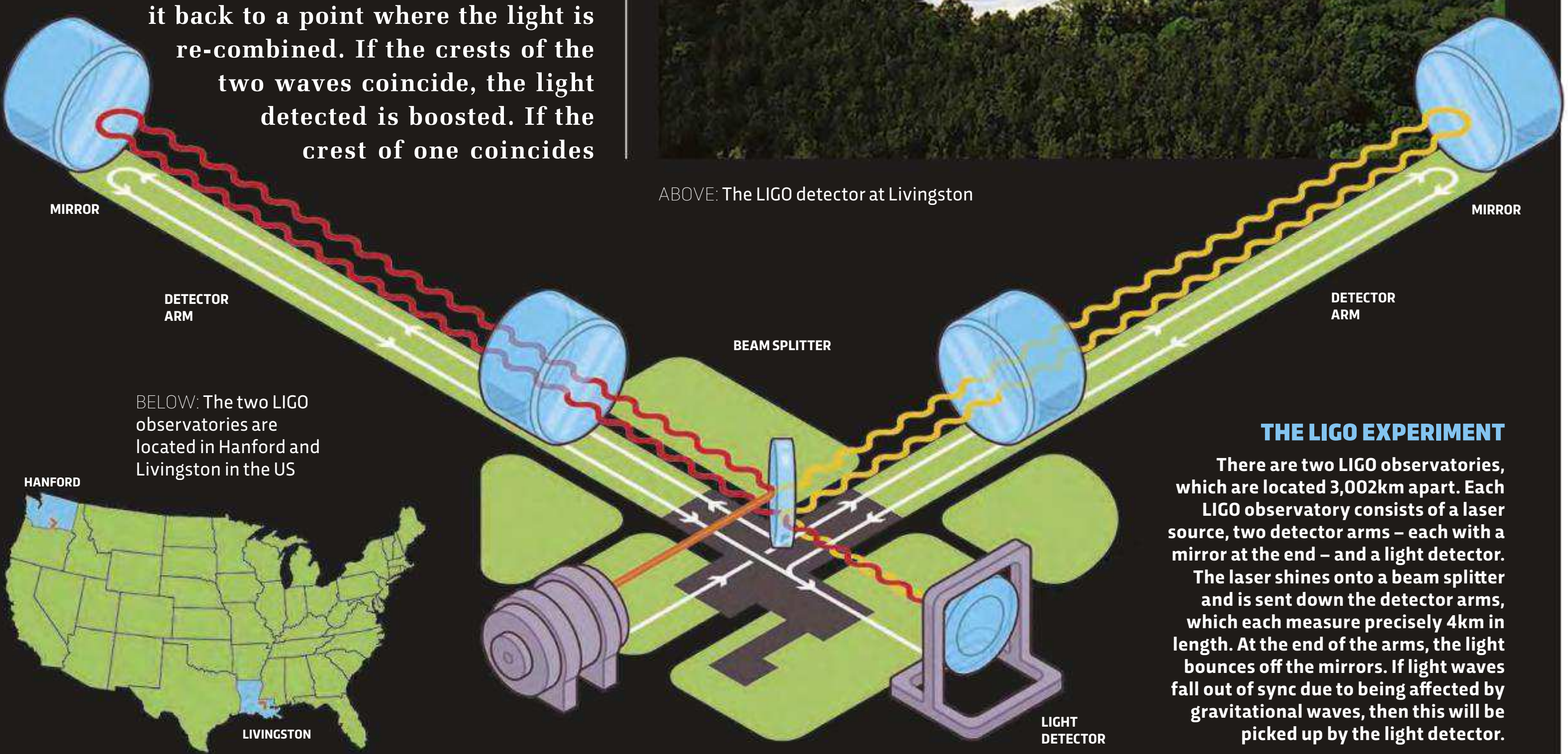
Number of years between the construction of the first LIGO prototype at the California Institute of Technology in Pasadena and LIGO's first detection of gravitational waves.

As gravitational waves pass, they stretch space in one direction and squeeze it in a perpendicular direction, then alternate repeatedly. The effect felt on Earth of the waves from a black hole merger is extremely small, typically a change in the length of a body by a mere billion billionth of its size. Consequently, the only way to detect such a small effect is with a big ruler. Enter the Laser Interferometer Gravitational Wave Observatory (LIGO). At Hanford in the state of Washington is a four-kilometre ruler made from laser light. Three thousand kilometres away at Livingston, Louisiana, is an identical ruler. Each site actually consists of two tubes 1.2 metres in diameter, which form an L-shape down which a megawatt of laser light travels in a vacuum more empty than space. At each end the light bounces off 42kg mirrors, suspended by glass fibres just twice the thickness of a human hair and so perfect they reflect 99.999 per cent of the light. It is the Lilliputian movement of these suspended mirrors that signal a passing gravitational wave.

LIGO splits laser light into two and sends it down each arm, where mirrors bounce it back to a point where the light is re-combined. If the crests of the two waves coincide, the light detected is boosted. If the crest of one coincides with the trough of the other, the light is cancelled out. Consequently, LIGO is sensitive to changes in the length of one arm relative to the other of a fraction of the wavelength of light. A lot of ingenuity is expended in getting that measurement down even further to a hundred-thousandth the diameter of an atom.

At 5:51am EDT on 14 September 2015, first in Livingston, then 6.9 milliseconds later in Hanford, the rulers repeatedly expanded and contracted by just a fraction, marking the first ever direct detection of gravitational waves.

ABOVE: The LIGO detector at Livingston

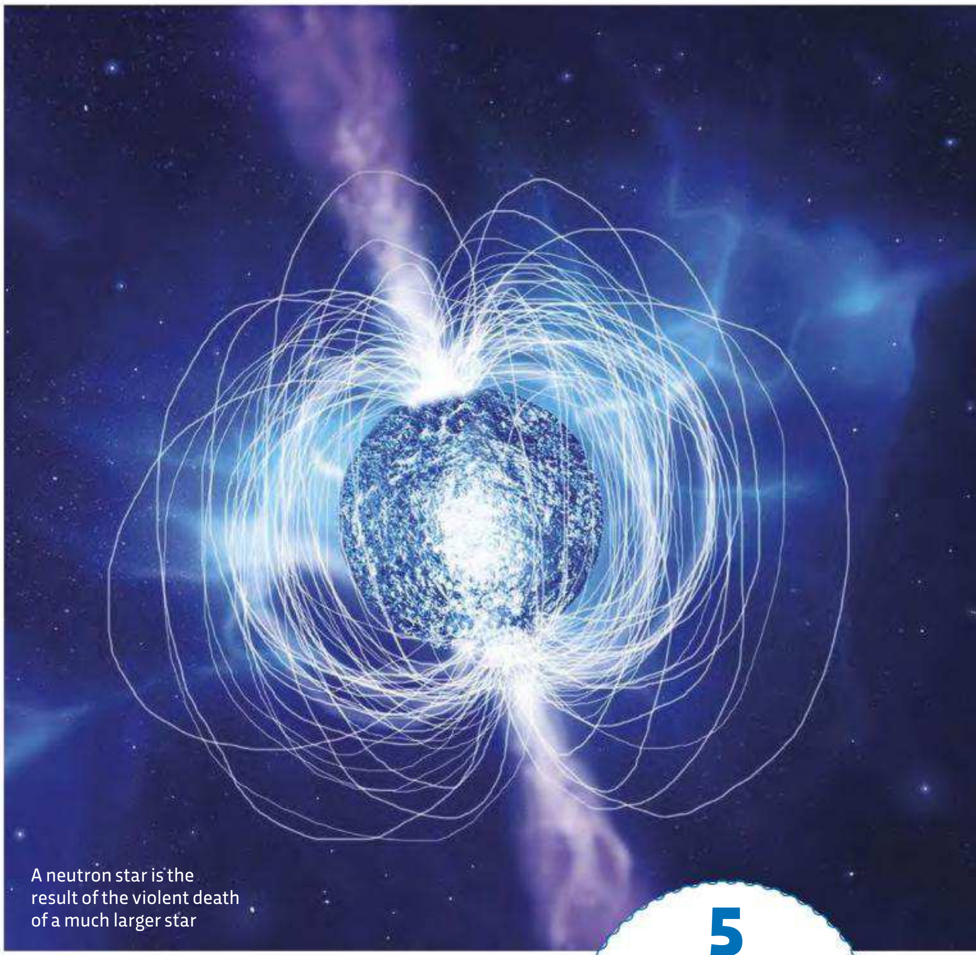



BELOW: The two LIGO observatories are located in Hanford and Livingston in the US

### THE LIGO EXPERIMENT

There are two LIGO observatories, which are located 3,002km apart. Each LIGO observatory consists of a laser source, two detector arms – each with a mirror at the end – and a light detector. The laser shines onto a beam splitter and is sent down the detector arms, which each measure precisely 4km in length. At the end of the arms, the light bounces off the mirrors. If light waves fall out of sync due to being affected by gravitational waves, then this will be picked up by the light detector.

# SOURCES OF GRAVITATIONAL WAVES


A neutron star is the result of the violent death of a much larger star

Neutron stars and black holes are the endpoints of the evolution of massive stars. When they explode as supernovas, paradoxically their cores implode. If the core is below a threshold mass, the stiffness of 'neutrons' can stop the shrinkage, leaving a star about the size of Mount Everest, but so dense that if you took a lump of its material measuring the same size as a sugar cube, it would weigh as much as the entire human race. If the core is above the threshold mass, no known force can stop the shrinkage and the star collapses to become a black hole.

Since most stars are born in pairs – our Sun being a rare exception – the expectation is that the most massive binaries end their lives as a pair of black holes, a pair of neutron stars, or a black hole orbiting a neutron star. The mere fact that the stars are orbiting each other – and changing their velocity, or accelerating – means that they radiate gravitational waves. This saps the stars of orbital energy, causing them to spiral in towards each other, at first very slowly, but, as time goes by, faster and faster.

Such an event, known as the 'binary pulsar', was observed for the first time in 1974, netting Russell Hulse and Joseph Taylor a Nobel prize for the first indirect detection of gravitational waves. The first direct detection of gravitational waves, however, was on 14 September 2015. The source was two black holes of 29 and 36 solar masses in a galaxy located 1.3 billion light-years away. It is plausible that they had been spiralling together for most of the age of the Universe. However, only as they swung around each other for their last dozen or so orbits, at half the speed of light, were their gravitational waves strong enough for us to detect on Earth. First, there was a 'chirp', repeated roughly every 15 milliseconds. Then there was a final powerful burst of gravitational waves as space-time buckled and contorted and the two holes kissed and coalesced into a single giant black hole.

Six bursts of gravitational waves have now been detected, five of which were from merging black holes. But, on 17 August 2017, for the first time, a signal was picked up from merging neutron stars.

**5**
Number of gravitational wave researchers so far awarded Nobel Prizes: Russell Hulse, Joseph Taylor, Rainer Weiss, Kip Thorne and Barry Barish.

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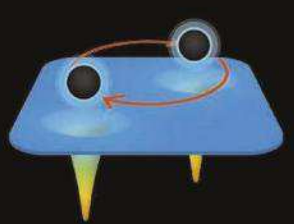
### BEFORE MERGER

**The two black holes were held in orbit around each other by their mutual gravitational pull. Their huge mass caused space-time to warp around them. Energy radiated away from them in the form of gravitational waves, leading to their orbits drawing closer.**

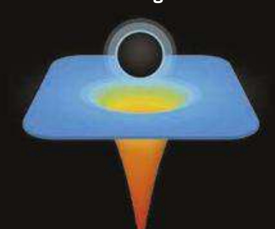


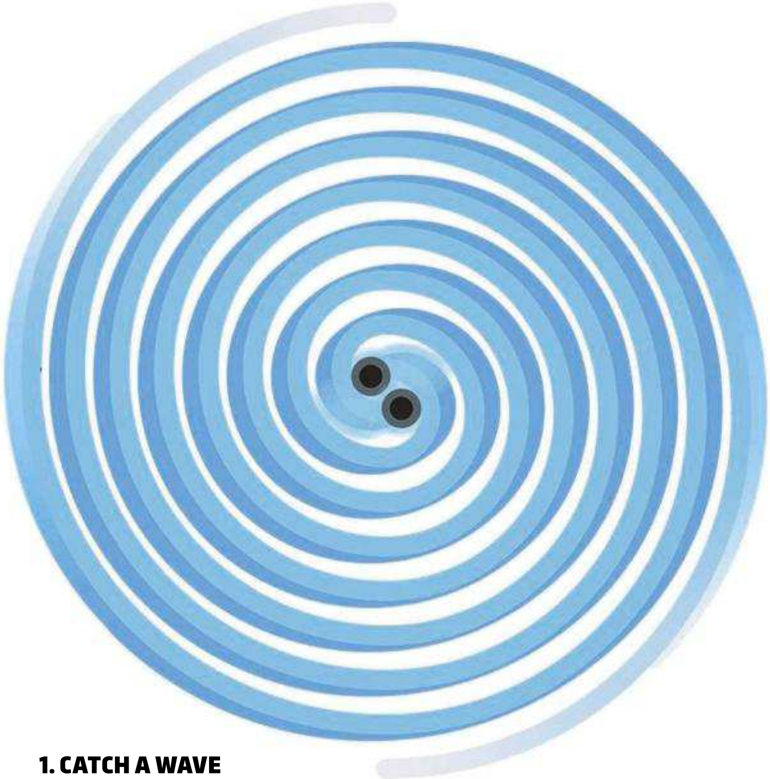
### DURING MERGER

**The black holes accelerated as they grew closer, reaching speeds close to the speed of light. Eventually, they merged into a single deformed black hole that radiated enormous amounts of energy as gravitational waves.**

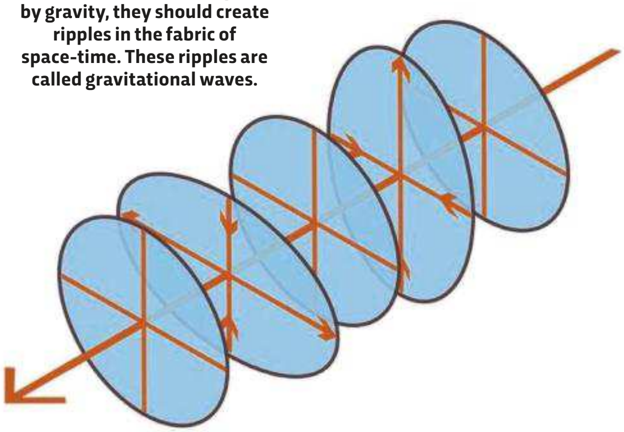
### AFTER MERGER

**Once the black holes had merged into a single entity, the system settled into equilibrium with a regular spherical shape, and the emission of gravitational waves dropped rapidly. This is known as the 'ringdown'.**

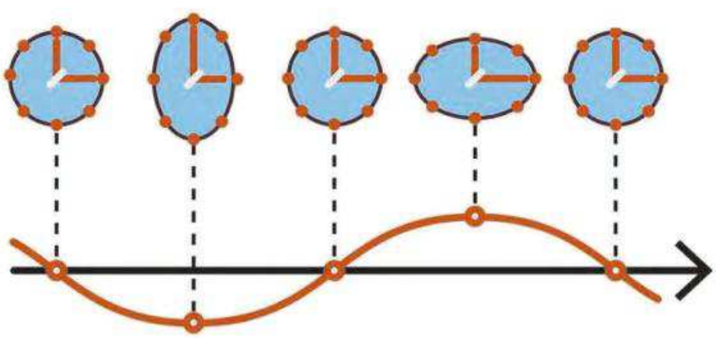




**1. CATCH A WAVE**
Einstein's General Theory of Relativity tells us that if two massive objects, such as two black holes, are bound together by gravity, they should create ripples in the fabric of space-time. These ripples are called gravitational waves.



**2. SPACE GYMNASTICS**
As a wave travelling at the speed of light passes through space-time, it first stretches space in one direction and squeezes it in the perpendicular plane, then reverses the process.



**3. DETECT IT**
On 14 September 2015, first in Livingston, then in Hanford, LIGO's arms repeatedly expanded and contracted by a hundred-thousandth the diameter of an atom, marking the first ever direct detection of gravitational waves.

# WHAT CAN GRAVITATIONAL WAVES TELL US?

Gravitational waves have the potential to point towards a better, deeper theory of gravity. We know that Einstein's theory breaks down in the infinitely dense 'singularity' found at the heart of a black hole and at the beginning of time in the Big Bang. The hope is that gravitational waves will lead us to a long-sought quantum theory of gravity.

They also have the potential to reveal the behaviour of super-dense matter inside neutron stars. Perhaps, even more excitingly, they could tell us about the birth of the Universe.

**The hope is that gravitational waves will lead us to a long-sought quantum theory of gravity**

In the standard picture, the Universe in its first split-second of existence went through an incredibly violent expansion known as inflation. This should have left a relic background of gravitational waves in today's Universe, which we may be able to detect and decode.

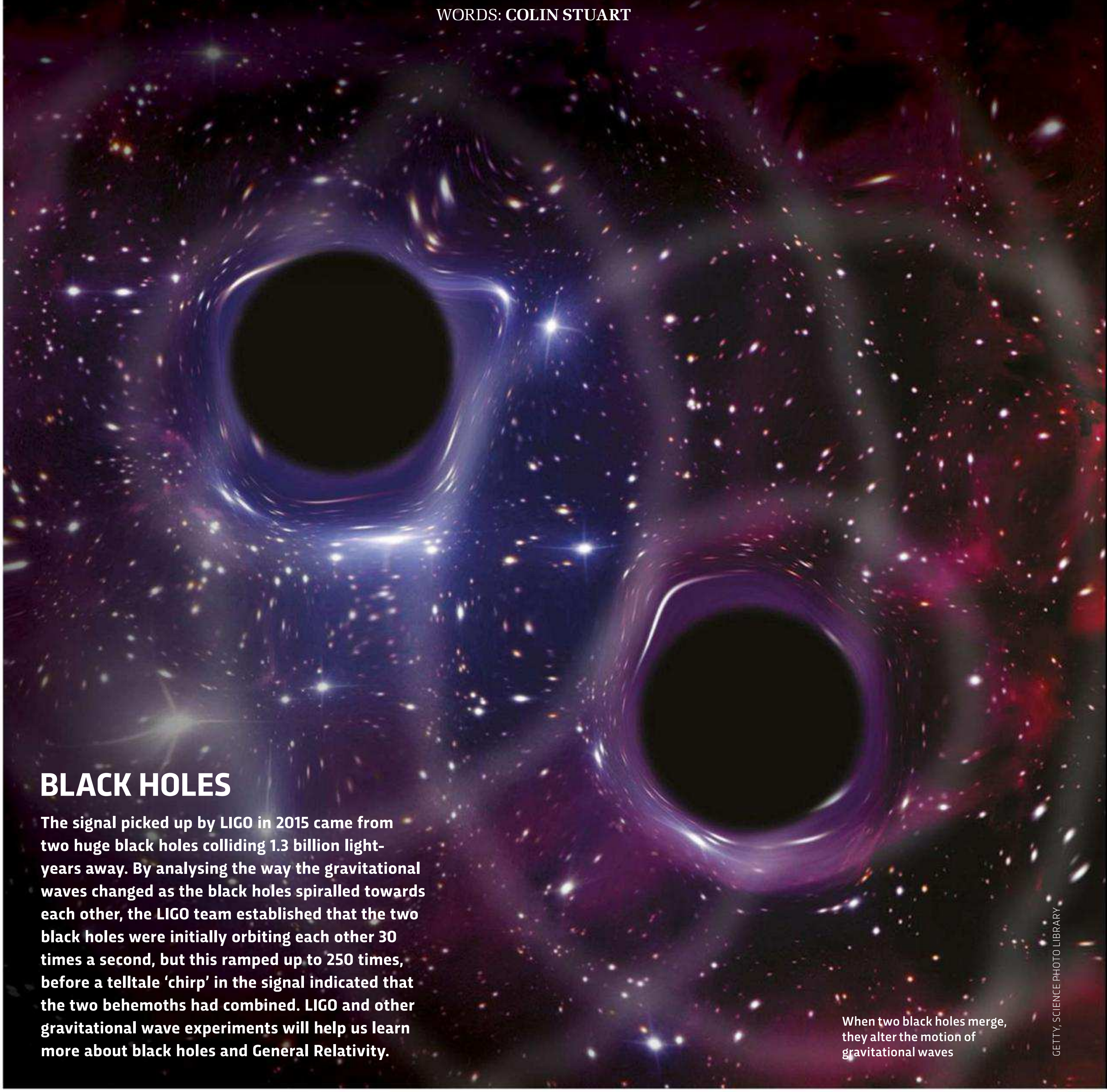
Gravitational waves truly provide us with a new 'sense'. We have always been able to see the Universe, with our eyes and telescopes. Now, for the first time, we can hear the Universe too. Gravitational waves are the 'voice of space'. So far, we have heard some sounds at the edge of audibility. Nobody knows what the cosmic symphony will sound like, but as we improve the sensitivity of gravitational wave detectors, we hope that we will discover things of which nobody has ever dreamed.

**Marcus Chown** is an award-winning cosmology writer and broadcaster. His latest book is *The Ascent Of Gravity*.

# MAKING WAVES

Now that we've detected gravitational waves, could they help us decipher some of the strangest phenomena in the cosmos?

WORDS: **COLIN STUART**



## BLACK HOLES

**The signal picked up by LIGO in 2015 came from two huge black holes colliding 1.3 billion light-years away. By analysing the way the gravitational waves changed as the black holes spiralled towards each other, the LIGO team established that the two black holes were initially orbiting each other 30 times a second, but this ramped up to 250 times, before a telltale 'chirp' in the signal indicated that the two behemoths had combined. LIGO and other gravitational wave experiments will help us learn more about black holes and General Relativity.**

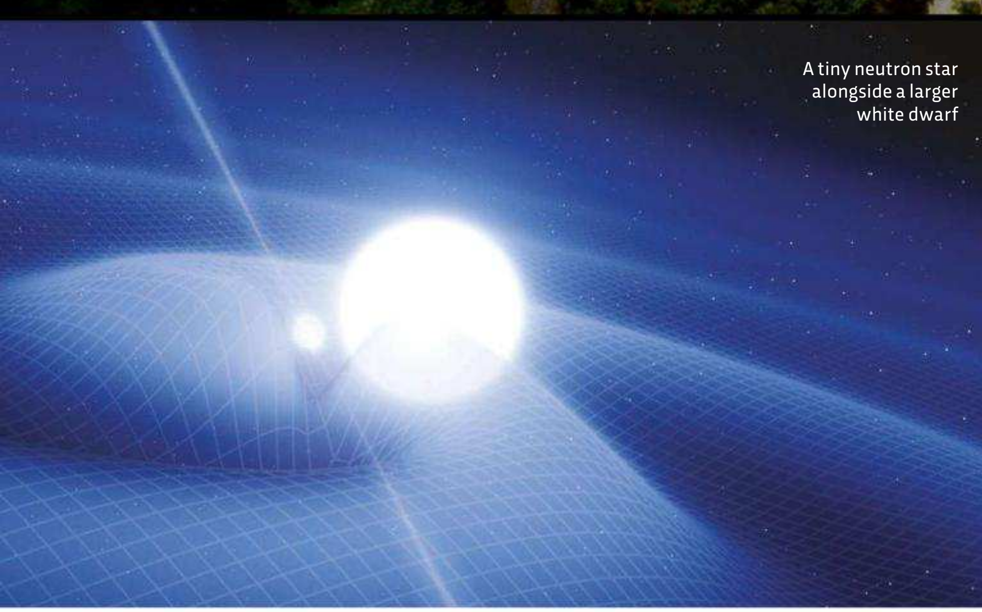
When two black holes merge, they alter the motion of gravitational waves

GETTY, SCIENCE PHOTO LIBRARY

Puerto Rico's Arecibo Observatory is used by NANOGrav astronomers to help them decipher galaxy formation

## GALAXY FORMATION

**The black holes observed by LIGO are tiny compared to those found at the centre of some of the most massive and distant galaxies. Such humongous beasts are thought to have been formed by a succession of previous mergers. Given that most galaxies are thought to host such supermassive black holes at their centre, systems such as OJ 287 could give us clues about the role that black hole mergers play in galaxy formation.**



A tiny neutron star alongside a larger white dwarf

## NEUTRON STARS

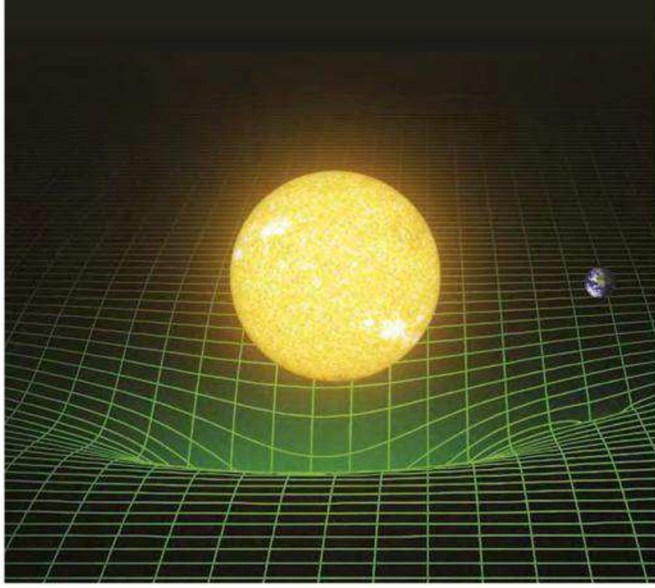
**Neutron stars are compact, city-sized stellar objects resulting from the explosive death of much larger stars. They are so incredibly dense that a neutron star the size of a golf ball would weigh around one billion tonnes. They spin extremely rapidly thanks to the power of the explosion from which they are created. It is thought that some rapidly rotating neutron stars have 'mountains' on their surface. These asymmetries should generate gravitational waves as the neutron star spins. Detecting such waves would be a real boon for theorists trying to understand how these mountains form.**

## DARK ENERGY

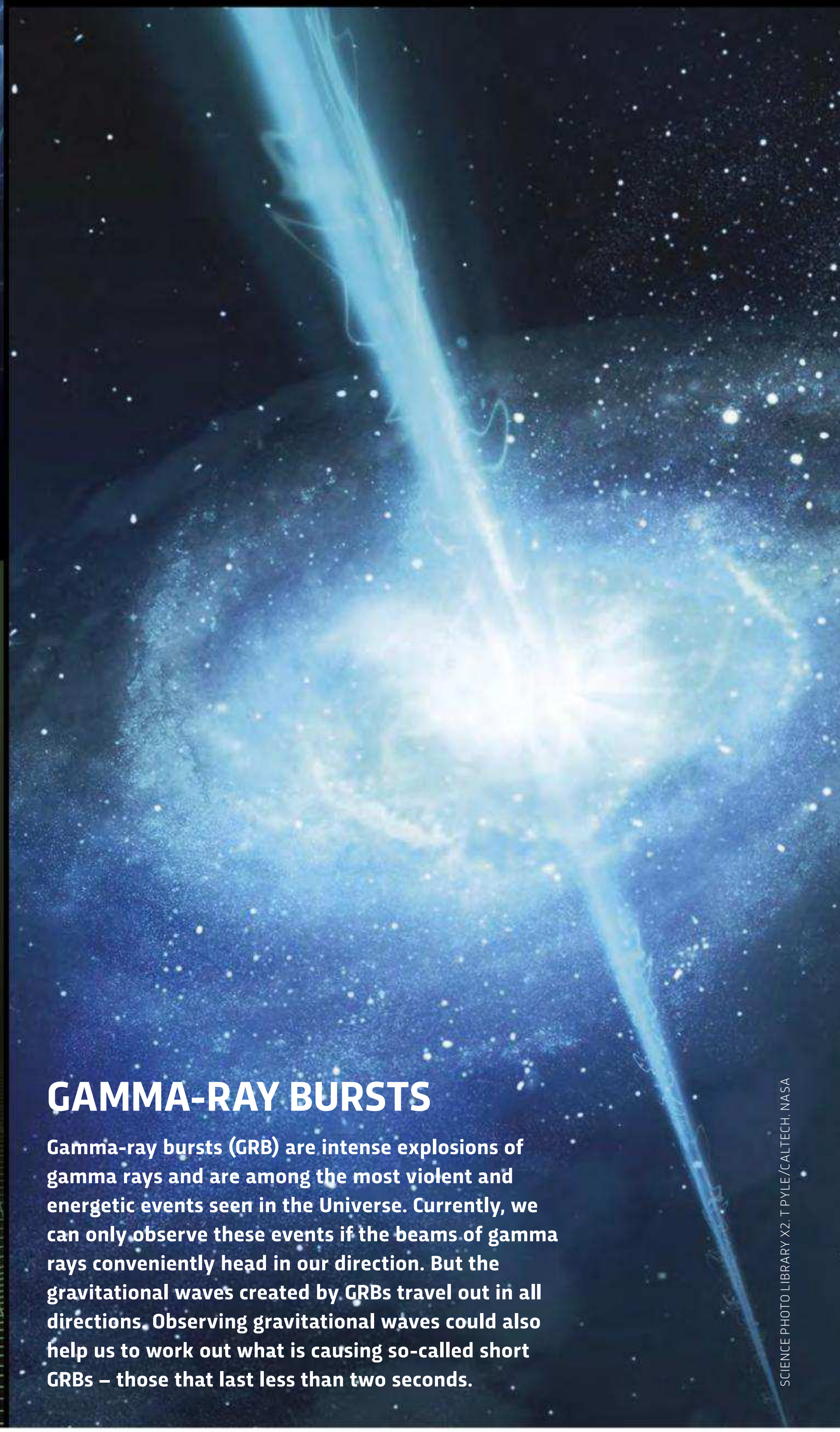
In the 1990s, astronomers found that the expansion of the Universe is speeding up. This was unexpected because it was thought that the expansion would be slowing down as the initial force of the Big Bang continued to fizzle out. It is thought that an invisible material, known as dark energy, is acting as a sort of anti-gravity and pushing clusters of galaxies apart. Gravitational waves could offer an alternative approach to measuring distance in space than the traditional method of detecting supernovas.

## GRAVITON

Perhaps the ultimate quest for physicists is to find a single, coherent theory that can explain all phenomena in the Universe that works for both General Relativity and quantum physics. Part of the problem is that in conventional General Relativity, gravitons are predicted to be massless (see page 35). By studying the behaviour of gravitational waves, researchers will be able to investigate the possibility that the graviton has mass, taking them a step closer to the elusive theory of everything.



**Gamma-ray bursts (GRB) are among the most violent and energetic events seen in the Universe**



## GAMMA-RAY BURSTS

Gamma-ray bursts (GRB) are intense explosions of gamma rays and are among the most violent and energetic events seen in the Universe. Currently, we can only observe these events if the beams of gamma rays conveniently head in our direction. But the gravitational waves created by GRBs travel out in all directions. Observing gravitational waves could also help us to work out what is causing so-called short GRBs – those that last less than two seconds.

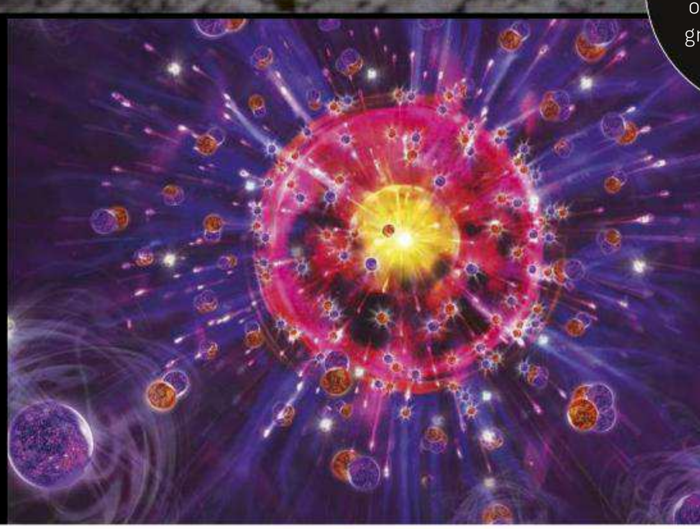
All objects, irrespective of their composition, fall with the same acceleration in a gravity field

## EQUIVALENCE PRINCIPLE

**LIGO's detection of gravitational waves ended a game of cosmic hide and seek that began 100 years ago when they were predicted by Einstein's General Theory of Relativity. Now that we have found them, gravitational waves could be used to test another cornerstone of Einstein's theory: the equivalence principle. Put simply, it says that all objects, irrespective of their composition, fall with the same acceleration in a gravity field.**

## COSMIC INFLATION

**When astronomers try to peer into the early Universe, they hit a smoke screen around 380,000 years after the Big Bang. At this time the Universe was composed of a dense sea of subatomic particles that prevented light from escaping, which means there's nothing to detect to tell us about the early Universe. Gravitational waves, however, would have been able to spread unhindered, allowing us to look back further than previously possible.**



BBC RADIO 4

Listen to an episode of *Inside Science* on gravitational waves *bbc.in/2HYqxct*

**Colin Stuart** is a freelance astronomy writer and author. His most recent book is *Physics In 100 Numbers*.

Inescapable: make the mistake of crossing a black hole's event horizon and the pull of its gravity becomes impossible to overcome

# BLACK HOLES

These weird, yet fascinating bodies are characterised by gravity so immense that nothing can escape

WORDS: **MARCUS CHOWN**

Black holes are regions of space where gravity is so strong that no matter or light can escape. Hence a black hole's blackness. The modern picture of black holes is provided by Einstein's General Theory of Relativity. The theory tells us that a mass like the Sun creates a valley in the space-time around it, into which other bodies fall. In this picture, a black hole is a bottomless well from which light cannot escape without being sapped of every last shred of its energy. At a certain point – the event horizon – the black hole's power is so strong that even a beam of light is helpless to resist the relentless pull of gravity. The curvature of space is so extreme here that all escape routes simply lead straight back into the black hole.

For reasons we don't fully understand, nature appears to have created two main classes of black holes: stellar-mass black holes and supermassive black holes, ranging in mass from millions of times the mass of the Sun to almost 50 billion times its mass. There is some evidence of the existence of a class of black holes between stellar-mass and supermassive, but so far astronomers have found very few of these intermediate mass black holes.

Stellar-mass black holes are the endpoint of the evolution of massive stars. But nobody knows the origin of supermassive black holes, or why there appears to be one in the heart of pretty much every galaxy, including our very own Milky Way. It's a chicken-and-egg puzzle. Does a galaxy of stars form first, and then later a supermassive black hole in its heart? Or does a supermassive black hole pre-date a galaxy and form the seed about which a galaxy of stars congeals?

The heating of matter as it swirls down onto a supermassive black hole creates an accretion disc so super-hot that it can pump out 100 times more energy than a galaxy of stars. This is the power source of active galaxies, the most energetic objects in the Universe.

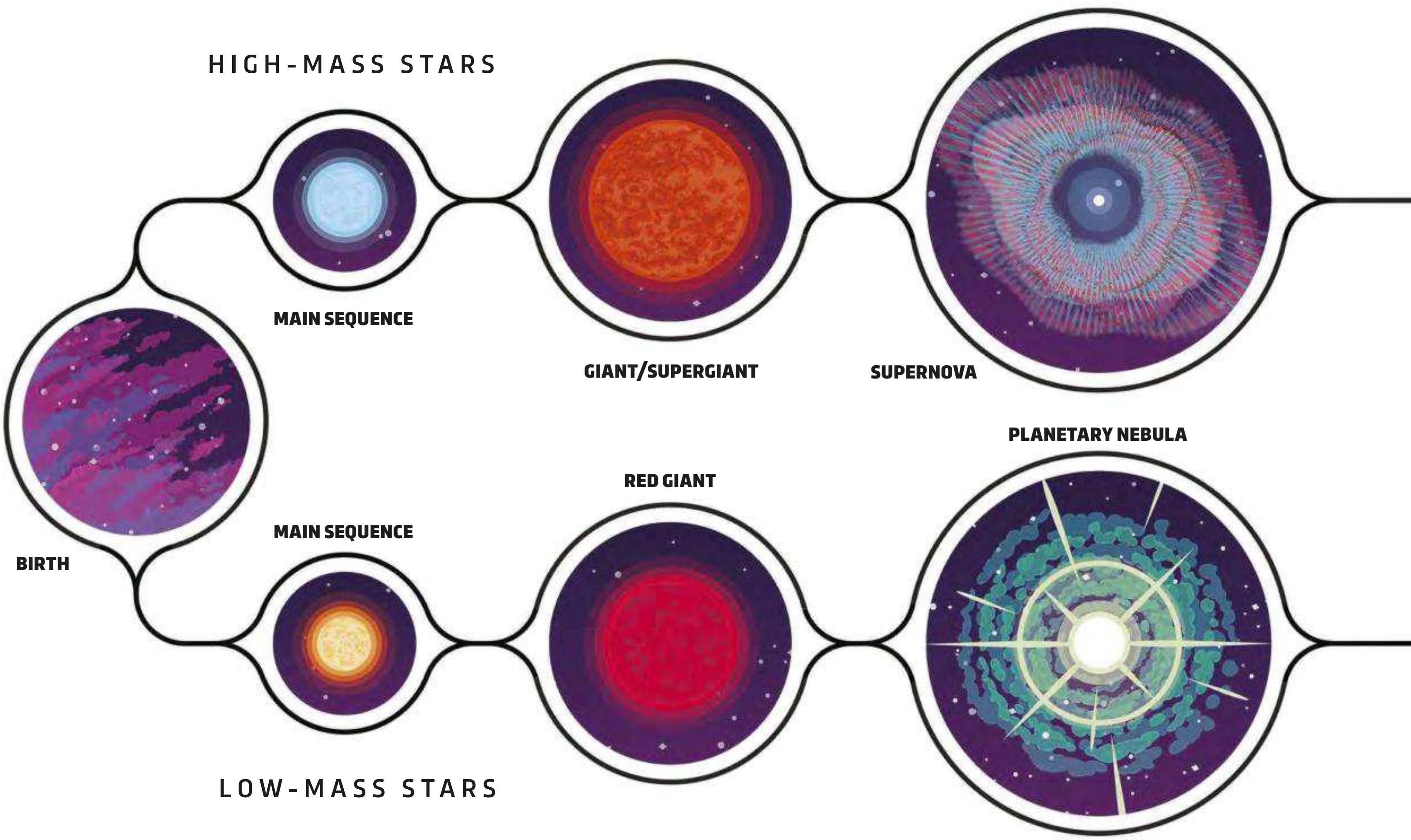
GETTY

# THE LIFE CYCLE OF A STAR

A star is born when a cold, dark cloud of interstellar gas and dust shrinks under its own gravity. As the gas is squeezed ever smaller, it gets hotter. Eventually, when the core temperature exceeds 10,000,000°C, nuclear reactions ignite and the ball of gas lights up as a star.

A star represents a temporary balance between the forces of gravity trying to shrink a ball of gas and its internal heat pushing outwards. The star fuses the cores, or nuclei, of hydrogen, the lightest atom, into the second lightest, helium. The mass difference between the initial and final product appears as the energy of sunlight, according to Einstein's famous formula $E=mc^2$. This conversion has an important effect on a star like the Sun. As helium is heavier than hydrogen, it falls to the centre. The nuclei of atoms repel each other and the bigger the nucleus, the stronger the repulsion. For two new nuclei to stick together and make a heavier nucleus, they must slam into each other at high speed, which in practice means at high temperature since temperature is a measure of microscopic motion. The core of the Sun will only ever be dense and hot enough to fuse hydrogen nuclei into helium. But this is not the case with more massive stars. Their cores eventually become dense and hot enough to fuse helium into carbon, carbon into oxygen,

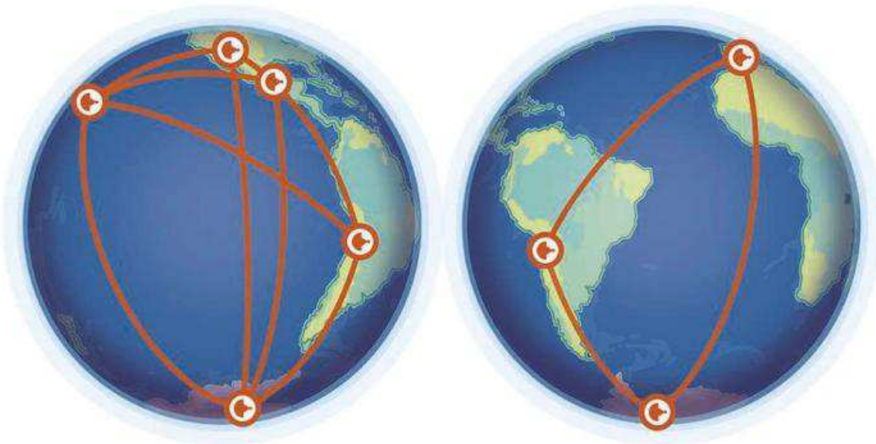
**A star represents a temporary balance between gravity trying to shrink a ball of gas and its internal heat pushing outwards**



oxygen into neon and so on. Such stars end up with an internal structure reminiscent of an onion, with the heaviest elements in the centre surrounded by concentric shells of less and less heavy elements.

The end point of this build-up process is iron. Its creation sucks nuclear energy from the core of the star. This causes the core to start shrinking, faster and faster, until a tiny, ultra-dense ball of neutrons, called a neutron star, is formed. In-falling material bounces off the neutron core, converting implosion into explosion – the explosion of a supernova that's so bright it can outshine an entire galaxy of stars. But if the core is massive enough, no known force can stop gravity crushing the core out of existence – in fact, crushing it all the way down to a point of infinite density known as a singularity. Cloaked in the impenetrable wall of an event horizon, this is a black hole.

ILLUSTRATIONS: RAJA LOCKEY



ABOVE: The Event Horizon Telescope is a network of telescopes at sites in Hawaii, California, Arizona, Mexico, Chile, Spain and the South Pole, which aims to photograph a black hole

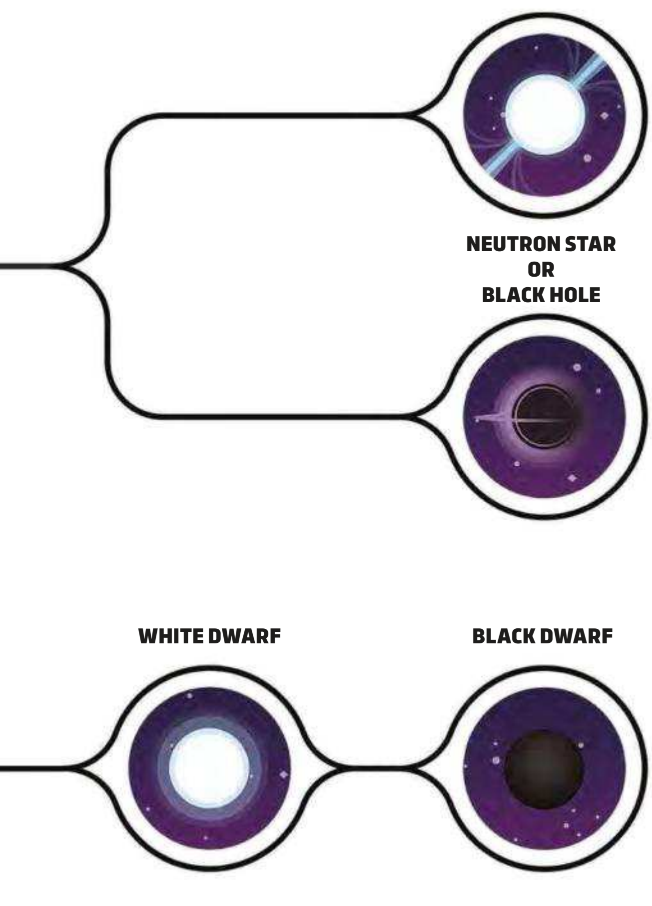
# THE QUEST TO PHOTOGRAPH A BLACK HOLE

Stellar-mass black holes are difficult to see in detail because, one, they're small and, two, they're black. The supermassive black holes in the hearts of galaxies are much bigger but unfortunately much farther away, making them appear small too. But one supermassive black hole is both big and near.

Sagittarius A*, 26,000 light-years away in the centre of our Milky Way, weighs in at 4.3 million solar masses. It's the target of the Event Horizon Telescope (EHT), an array of radio telescopes scattered across the globe. The radio signals recorded at each site are combined on a computer at the Haystack Observatory in Massachusetts, to simulate a giant dish the size of the Earth. The bigger a dish is and the shorter the observing wavelength (EHT is using 1.3mm) the more it can zoom in on details in the sky.

The challenge is to image Sagittarius A*'s event horizon. What astronomers want to know is whether the event horizon behaves as Einstein predicted or even whether it exists. Just before his death, Stephen Hawking suggested that it might not. "An image would symbolise a turning point in our understanding of black holes and gravity," says EHT director Shep Doeleman.

The telescopes have been capturing images for the last couple of years, and the team is now analysing them, so we may see the first image of a black hole event horizon this year. Almost certainly, it will be an image to rival the double helix of a DNA spiral or the Apollo 8 image of the Earth rising above the Moon.




LEFT: Stars are born when a gas cloud collapses and matter accumulates on a protostar. A high-mass star is 10-150 solar masses (one solar mass = the mass of our Sun), a low-mass star is 0.08-10 solar masses. The main sequence takes up 90 per cent of a star's life – the Sun is currently at this stage. High-mass stars have shorter lives and will become giants or supergiants before exploding into a supernova, where all but 10 per cent of the original mass is ejected. The star's core will then collapse. Depending on the size of the core's mass, it will either become a neutron star or a black hole. Low-mass stars have longer lives. After the main sequence, they'll become red giants. Eventually, the outer layers of gas will be ejected and the star's core will contract to form a white dwarf. Theoretically, the star could then cool to form a black dwarf, but the Universe is still too young for this to have been proven.

**6**
Diameter in kilometres of the black hole that would form if the matter of the Sun could be squeezed hard enough.

**4.3 million**
Mass in multiples of the Sun's mass of Sagittarius A*, the giant black hole at the heart of our Milky Way.

**1.8**
Diameter in centimetres of the black hole that would form if the matter of the Earth could be squeezed hard enough.

**40 billion**
Mass in Suns of the biggest known black hole in the Universe: S5 0014+81.

**1**
Diameter in metres of the Jupiter-mass black holes left over from the Big Bang, which some have suggested could make up the Universe's invisible dark matter.

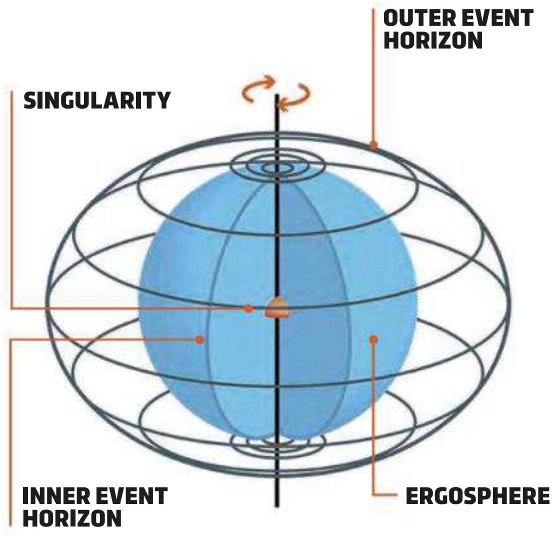
**2 trillion**
The probable number of supermassive black holes in the Universe: one in each galaxy.

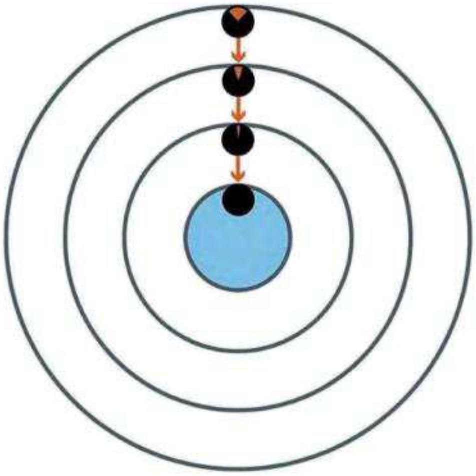
# THE ANATOMY OF A BLACK HOLE

Once a massive star has shrunk to form a black hole, nothing is left (as far as we know) but a bottomless pit of space-time. A black hole is surrounded by an event horizon, an imaginary membrane that marks the point of no return for in-falling matter and light. Inside the event horizon, at the heart of the black hole, Einstein's General Relativity predicts the existence of a point of infinite density called a singularity. Yet once you reach the singularity, Einstein's theory – and physics as we know it – breaks down. Perhaps a new, quantum theory of gravity is needed to tell us what really exists there.

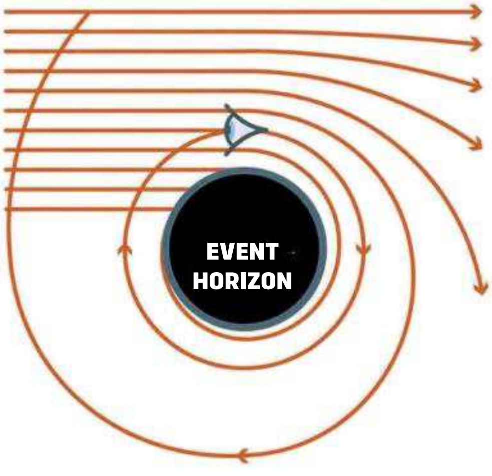
To give you an idea of what that entails, imagine an astronaut falling feet first into a black hole. When she is at a circumference corresponding to one and a half times the circumference of the black hole, gravity is so strong that it bends light into a circle around the hole, so she'll be able to see the back of her head! Near a stellar-mass black hole, the huge difference in gravity between the astronaut's head and feet will tear her apart before she reaches the event horizon. But this tidal effect is negligible near a supermassive black hole and the astronaut can cross the event horizon with no ill-effect.

Einstein's theory predicts that time flows more slowly in strong gravity. So, if you were to observe the astronaut falling into the black hole from a safe distance, she'd appear to move in ever slower motion then stop altogether at the event horizon. Although she'd fall through into the hole, never to appear again, her image would be frozen on the event horizon, gradually fading as the light from it struggled to climb out.

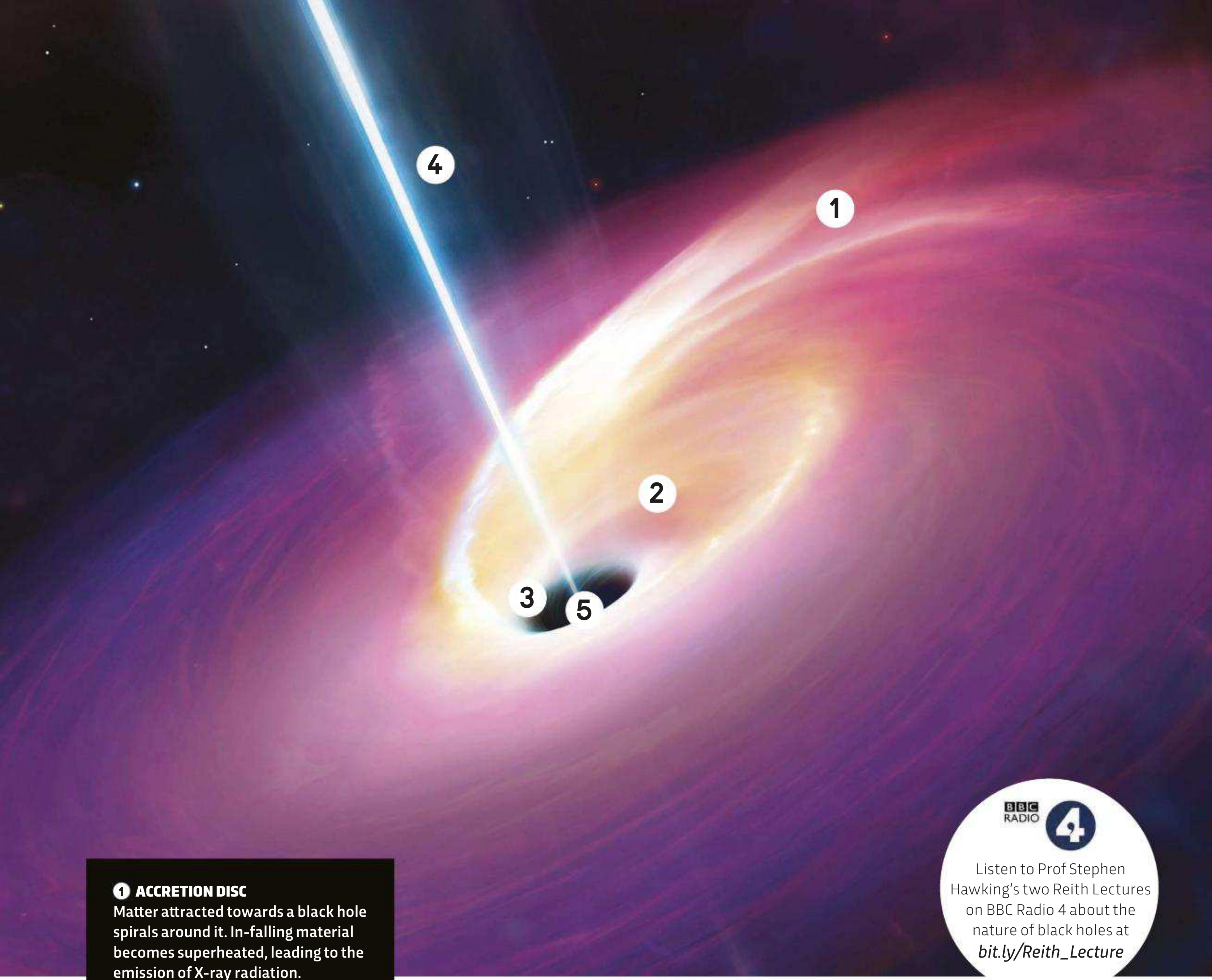


ABOVE: As a light source (the black circle) nears the event horizon, fewer and fewer photons are able to escape (the orange segments) from the black hole's gravitational clutches. Once the event horizon is reached no photons are able to escape




ABOVE: The gravity of a black hole is so immense that it bends light into a circle round the hole. This means that someone falling in would be able to see the back of their own head




**1 ACCRETION DISC**
Matter attracted towards a black hole spirals around it. In-falling material becomes superheated, leading to the emission of X-ray radiation.

**2 ERGOSPHERE**
The region beyond the event horizon of a black hole where gravity starts to have an influence on objects.

**3 EVENT HORIZON**
The point at which the speed required to escape from the black hole exceeds the speed of light. Effectively the point of no return.

**4 JET**
Jets of matter are thought to form when material in the accretion disc interacts with magnetic fields close to the event horizon.

**5 SINGULARITY**
All matter falling into a black hole gets crushed into this infinitely small and dense point.

GETTY ILLUSTRATIONS: RAJA LOCKEY

BBC RADIO 4

Listen to Prof Stephen Hawking's two Reith Lectures on BBC Radio 4 about the nature of black holes at *bit.ly/Reith_Lecture*

In the case of a rotating, or Kerr, black hole, there's a twist. In effect, Kerr black holes have two horizons – an inner horizon and an outer one. When the astronaut crosses the outer one and enters the ergosphere, she's dragged around by a tornado of space-time. At this point she can still gain energy from the black hole's rotation and be ejected from the black hole. But once she crosses the inner event horizon, however, there's no going back.

Nobody knows what the inside of a black hole looks like. But space and time are so distorted by them that they swap places. The singularity therefore exists not across an interval of space but in the falling astronaut's future. As such, she can no more avoid reaching it and being crushed to death than you can avoid tomorrow.

**Marcus Chown** is an award-winning cosmology writer and broadcaster. His latest book is *The Ascent of Gravity*.

# HAWKING'S FINAL PREDICTION

Stephen Hawking was working on unlocking the Universe's secrets right up until the very end and spent his final months wrangling with the problems posed by the concept of a multiverse

WORDS: **MARCUS CHOWN**

Einstein's theory of gravity breaks down in the face of a singularity, such as those found in the hearts of black holes and the Big Bang. As a result we know Einstein's theory is an approximation of a deeper theory, one that may explain everything.

The hope among physicists is that this 'theory of everything' will unite the theory of the big (Einstein's theory of gravity) with the theory of the small (quantum theory). In 1974, Stephen Hawking's genius was to find a place – the event horizon surrounding a black hole – where, despite lacking a theory of everything, he could nevertheless predict something about the world: Hawking radiation (a phenomenon that permits black holes to glow despite their gravity being strong enough to prevent light escaping them). In the last year of his life, he claimed to have found another location where it's possible to make a sensible prediction: the Big Bang itself.

Hawking and his colleague, Thomas Hertog of the University of Leuven in Belgium, initially aimed to put Hawking and James Hartle's no-boundary Universe concept of the early 1980s (which attempts to explain how nothing could preceed the Big Bang) on a firmer theoretical

WIL STEWART/UNSPLASH, STEPHEN HAWKING FACEBOOK, SCIENCE PHOTO LIBRARY


ABOVE: Stephen Hawking's collaboration with Thomas Hertog, of Belgium's University of Leuven, resulted in a more manageable concept of the multiverse

BELOW: The Universe's expansion is analogous to an inflating balloon – galaxies recede from each other as if they are situated on the fabric of the balloon as it's gradually inflated

footing. To their delight, they discovered that their model predicted that our Universe came into existence with a phase of inflation, the super-fast cosmic expansion believed to have occurred in the Universe's first split-second and which is a key component of today's standard Big Bang model.

#### UNIFORM TEMPERATURE

Inflation explains why today's Universe has the same temperature everywhere even though, in the Big Bang, far-flung places were not in contact with each other and so couldn't have exchanged heat to equalise their temperatures. A cosmos that expanded faster than expected early on in its life could have started out smaller – allowing the exchange of heat – while still reaching its current size in the 13.82-billion-year age of the Universe.

Inflation was driven by a high-energy state of the vacuum with repulsive gravity, which caused it to expand and grow. The more of it there was, the greater the cosmic repulsion and the faster it expanded. But the inflationary vacuum was a quantum thing, which meant it was fundamentally unpredictable and decayed at random places into a normal, everyday vacuum. Think of bubbles forming in an ever-expanding ocean. Inside each bubble, the energy of the inflationary vacuum has to go somewhere. And in the case of the very earliest moments of our Universe's existence it went into creating matter and heating it to a ferociously high temperature. It created a big bang. In this scenario, big bangs go off constantly, like stuttering firecrackers, all over the inflationary vacuum. We live inside one such big bang bubble.

The inflationary vacuum, however, is created faster than it's eaten away, so inflation, once started, never finishes. It's eternal. This creates an ensemble, or multiverse, of universes.

**In the last year of his life, Hawking claimed to have found another location where it's possible to make a sensible prediction: the Big Bang itself**

The only framework so far that unites quantum theory and relativity is string theory, which views the fundamental building blocks of matter as ultra-tiny vibrating strings of mass-energy. Hopes that string theory might point to a theory of everything were dealt a blow when it was discovered there was not one but at least 10,500 string vacua, each with different fundamental particles and forces.

Hawking and Hertog, and others, equate the string vacua with the multiple universes of eternal inflation. But this makes cosmology mind-bogglingly complex and practically untestable. "We therefore set out to tame the Multiverse," says Hertog.

#### THOSE LEFT BEHIND

Hawking and Hertog noted that Einstein's theory of gravity in four dimensions of space-time is thought to be equivalent to string theory in three dimensions. Using this conjecture, they could make the Multiverse more manageable. They found that this constraint culled the wilder universes, leaving behind only those that are similar to ours, greatly reducing the number of universes in the Multiverse.

Until now, theorists have faced the problem of explaining what we see in our Universe statistically – that is, by showing that we live in one of the most common universes of the Multiverse, the one with the most common mass for the electron, strength of gravity and so on. This is a daunting, if not impossible, task, given the large number of universes in the Multiverse. But Hawking and Hertog say that this reasoning may be much easier with their reduced Multiverse.

"We may be able to explain our Universe despite not being able to observe the other regions of the Multiverse," says Hertog. "With our paper we take a step towards turning the no-boundary model of the Big Bang into a predictive framework for cosmology."

ABOVE RIGHT: Inflationary expansion is faster than the speed of light, and could lead to the formation of bubble universes that would be isolated from each other

ABOVE FAR RIGHT: Bubble universes may have formed in the early Universe, where false vacuums created a repulsive force that caused an incredibly rapid expansion

BELOW RIGHT: The theory of everything remains hypothetical but attempts to unify quantum field theory and general relativity

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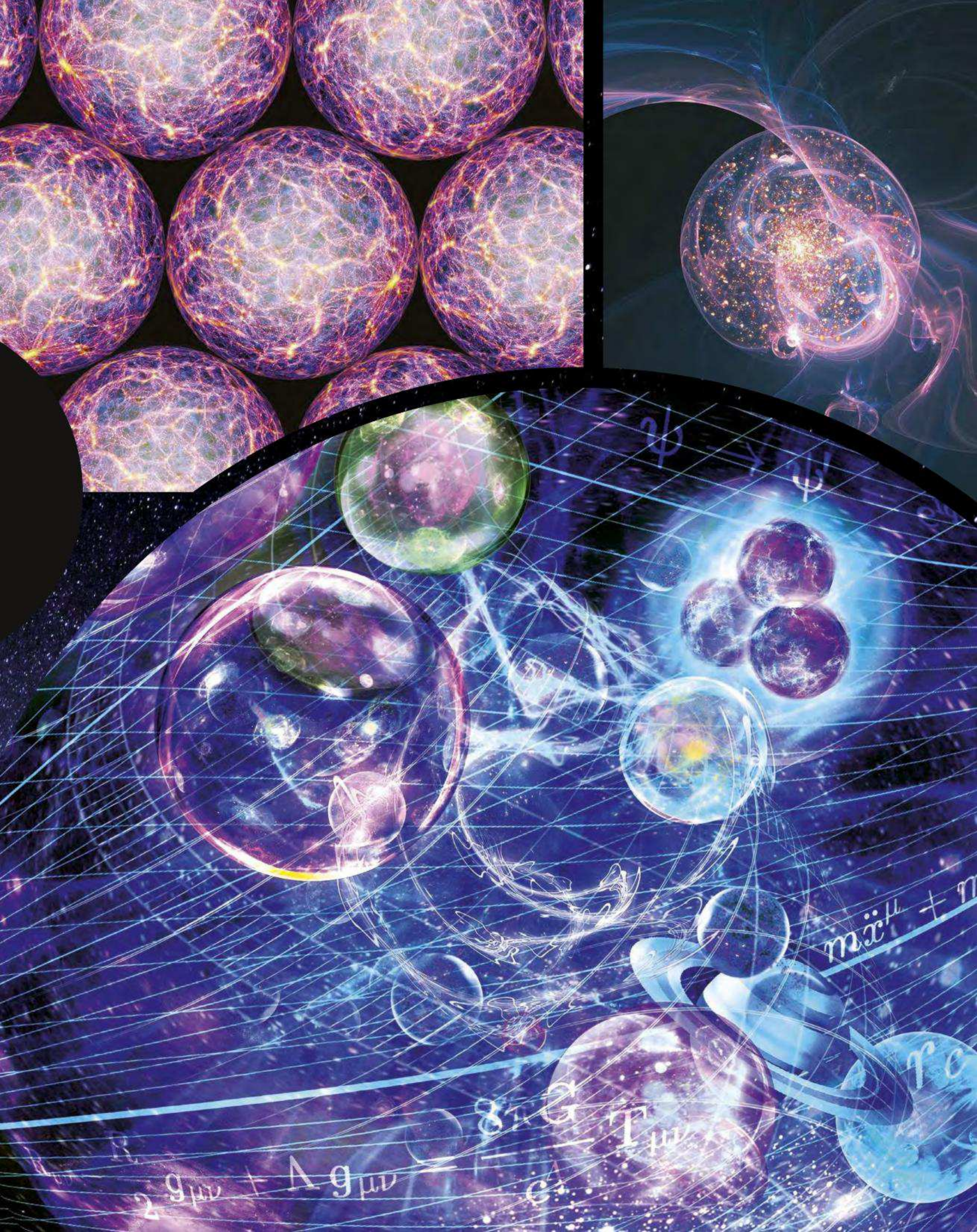
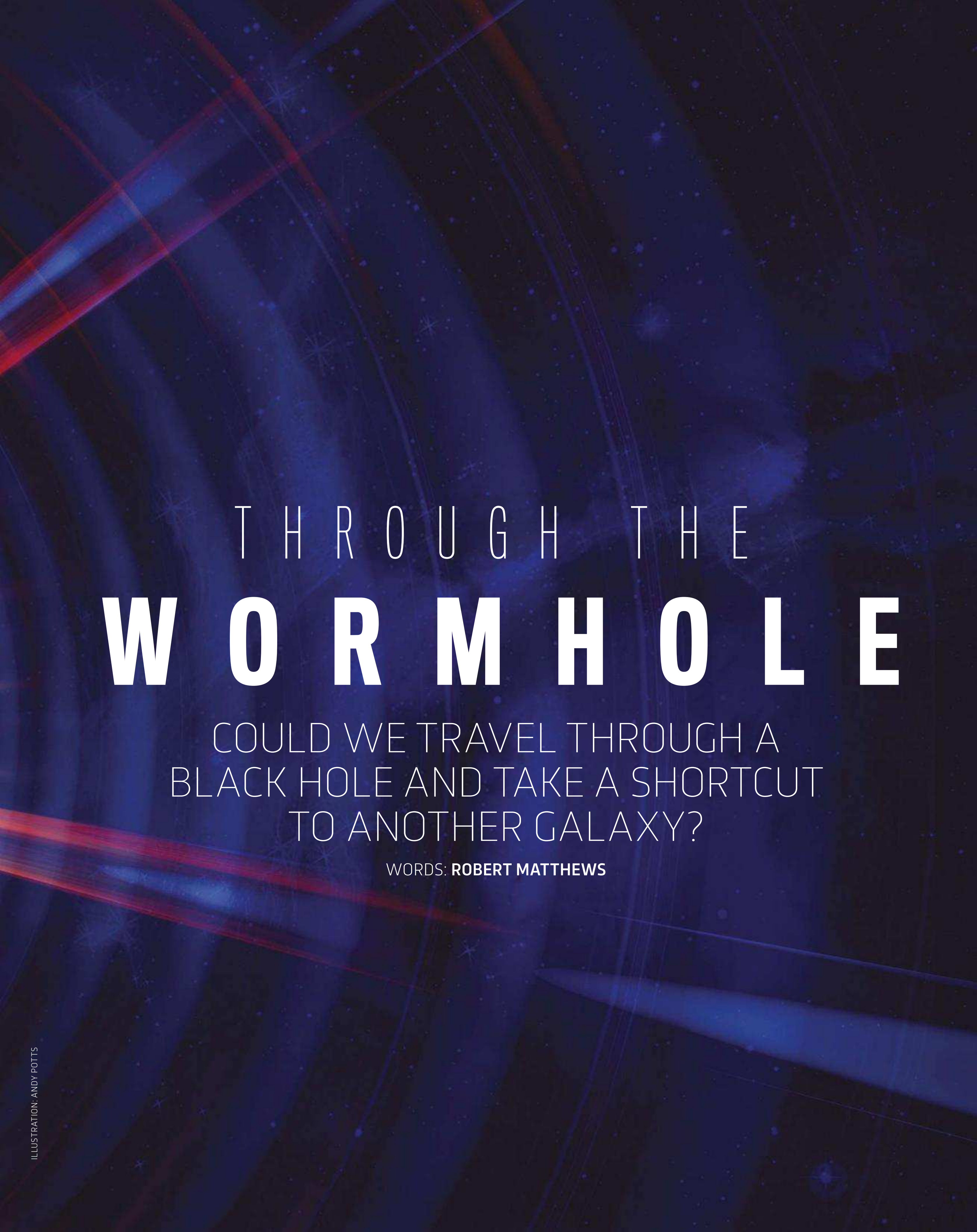
**Marcus Chown** is an author and former radio astronomer. His latest book is *The Ascent of Gravity*.





# THROUGH THE WORMHOLE

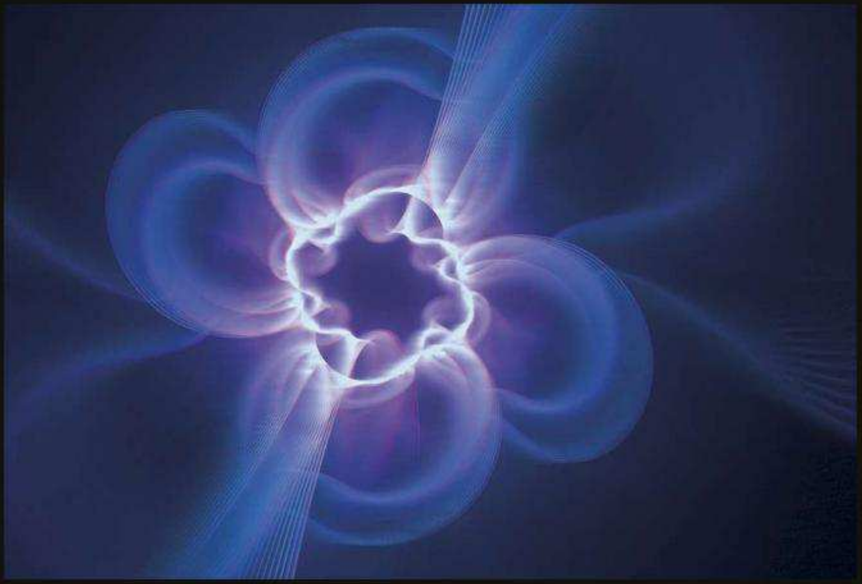
## COULD WE TRAVEL THROUGH A BLACK HOLE AND TAKE A SHORTCUT TO ANOTHER GALAXY?

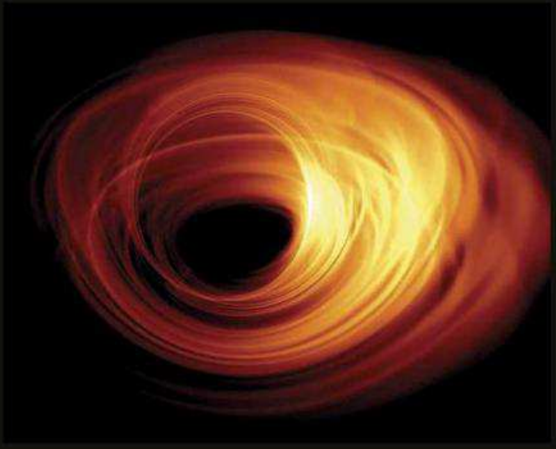
WORDS: **ROBERT MATTHEWS**

ILLUSTRATION: ANDY POTTS

Ever since a trip through a wormhole was first portrayed in *2001: A Space Odyssey* 50 years ago, the idea of them has captured the public imagination. And small wonder: they're the ultimate form of cosmic travel: a way of zipping across galaxies in an instant.

But while wormholes are a staple of science fiction, for scientists they're a source of endless frustration. Not because the idea is ridiculous, but because it isn't. The astonishing fact is that wormholes are a natural consequence of current theories of gravity, and were investigated by Einstein over 80 years ago. Ever since, researchers have been trying to find out if they could be a reality.





ABOVE: Dark energy, as visualised here, is responsible for the expansion of the Universe

RIGHT: Artist's impression of the event horizon – the point of no return – of the black hole at the centre of our Galaxy

And now they've made a major breakthrough – one that exploits deep connections between the nature of space and time and the laws of the subatomic world. The result is a new understanding of exactly what's required to make a real-life wormhole.

**SHORTCUTS THROUGH SPACE**

Einstein first investigated the properties of wormholes with his colleague Nathan Rosen in 1935, using his theory of gravity known as General Relativity. They found that what we now call a black hole could be connected to another via a tube-like 'throat'. Now called the Einstein-Rosen bridge, this seemed to open the way to taking shortcuts through space and time, entering a black hole in one part of the Universe and emerging from another perhaps millions of light-years away, but without taking millions of years to do so – thus effectively travelling faster than the speed of light.

It was a stunning idea, but in the early 1960s it was dealt a severe blow by John Wheeler, the brilliant US physicist who first coined the terms black hole and wormhole. Together with fellow theorist Robert Fuller, he showed that the Einstein-Rosen bridge would collapse almost as soon as it formed. As Dr Daniel Jafferis, associate professor of physics at Harvard University explains: "We could jump in from opposite sides and meet in the connected interior, but then we would both be doomed."

Jafferis is one of an elite group of theorists around the world searching for ways to dodge this problem. For years, the most promising idea has been to support the bridge using a type of exotic matter with negative energy. As its name suggests, this is pretty weird stuff – so weird it's capable of bending the normal rules of gravity. While ordinary matter always generates a gravitational pull, the negative energy produced by this exotic matter generates an anti-gravitational repulsion. Amazingly, such energy is known to exist. In the 1990s, astronomers discovered that the whole Universe is expanding under the anti-gravitational effect of this dark energy. As we saw on page 68, the exact origins of dark energy are as yet unknown. The same goes for the exotic matter – no one has any idea how to create the stuff,

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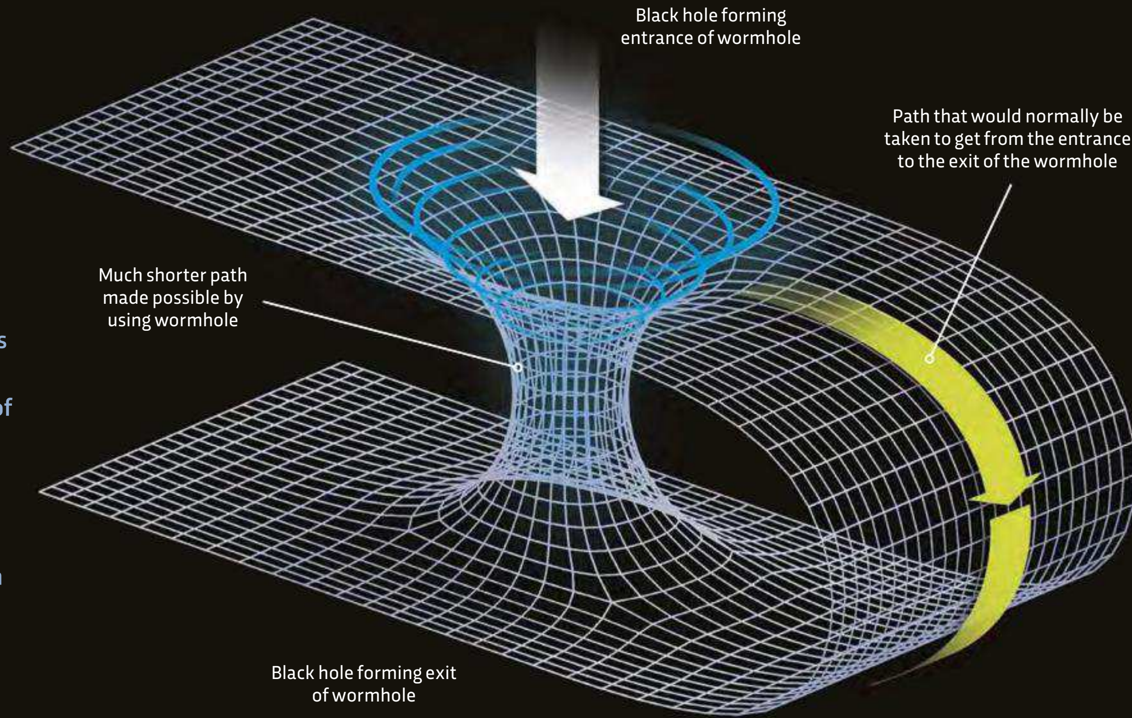
# WORMHOLE ANATOMY

TWO METHODS OF SKIPPING THROUGH SPACE

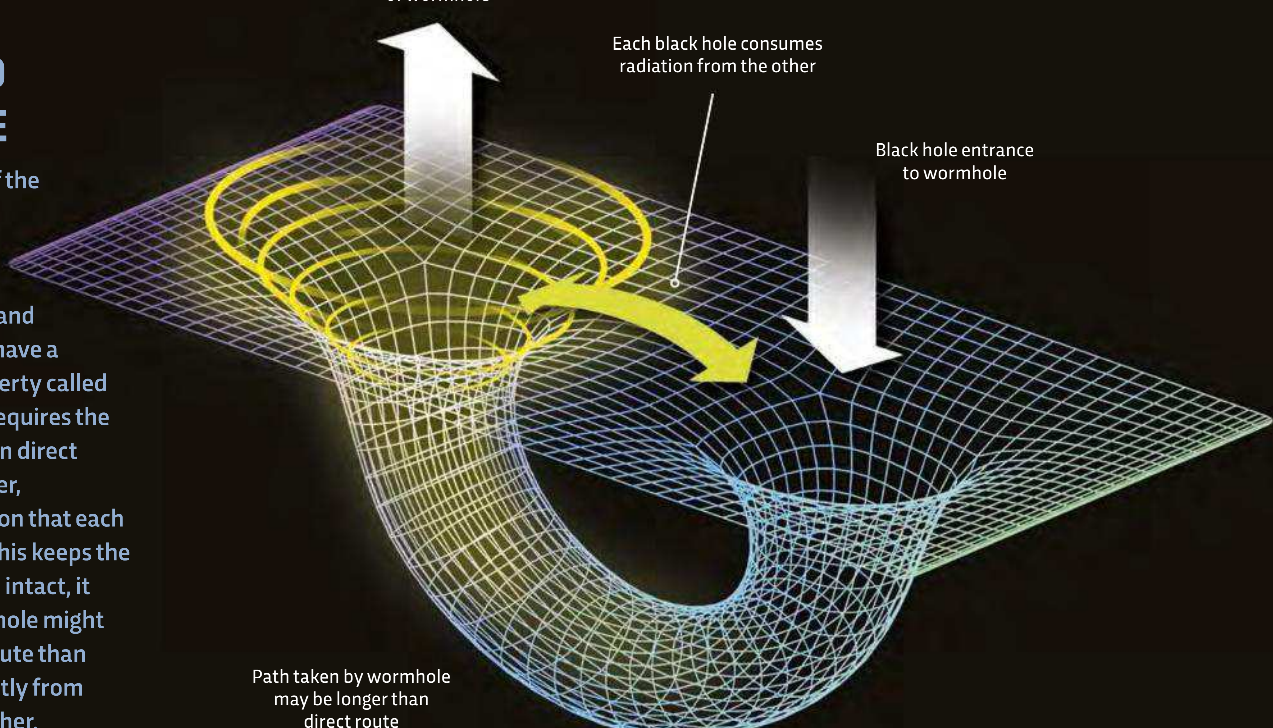
## 1 THE CLASSIC BUT DEADLY EINSTEIN-ROSEN WORMHOLE

This is the original wormhole version investigated by Einstein. It seems to offer a shortcut through space and time, and thus the possibility of effectively travelling faster than the speed of light. But the Einstein-Rosen bridge inside the wormhole immediately collapses and traps travellers inside, unless it's supported by some strange form of material that generates negative energy.




## 2 THE ENTANGLED WORMHOLE

The deadly collapse of the Einstein-Rosen bridge could be prevented if the black holes forming the entrance and exit of the wormhole have a special quantum property called 'entanglement'. This requires the two black holes to be in direct contact with each other, consuming the radiation that each spews out. But while this keeps the Einstein-Rosen bridge intact, it also means the wormhole might actually be a longer route than simply travelling directly from one black hole to another.



let alone use it to keep a wormhole open long enough to fly through.

**THE WORM HAS TURNED**

But now the debate over such so-called traversable wormholes has taken a radical new turn. It follows the discovery of a new way of keeping the bridge intact based on a surprising link between wormholes and quantum theory. It emerged during attempts to solve a problem of what happens to objects that fall into a black hole?

We know from page 70 that there's no escaping a black hole once you're inside it: the pull of gravity is too strong even for light to break free. Yet the late Stephen Hawking famously showed that a black hole doesn't last forever, but eventually explodes in a burst of intense radiation, leaving no trace of whatever fell into it. The trouble is, this contradicts one of the key principles of quantum theory, which states that information can never be destroyed. Black holes, however, seem quite capable of utterly destroying information about what they've consumed. This is the notorious black hole information paradox and it hints at a big gap in our understanding of how the Universe works.

For decades, Hawking and many others tried to resolve the paradox without success. But now there's growing excitement that the answer has been found. And it lies in the ability of wormholes to provide a way out of black holes. Put simply, theorists think the supposedly inescapable boundary of a black hole – the event horizon – is riddled with tiny wormholes that allow information to seep out, along with the radiation that Hawking showed

Black holes will destroy anything that is drawn into them, like this star. Yet wormholes could provide a way out

## They're the ultimate form of cosmic travel: a way of zipping across galaxies

destroys black holes. This, in turn, has led to new insights into the nature of wormholes, and whether they can be traversed.

Until now, the only known way to traverse a wormhole was to stop the Einstein-Rosen bridge collapsing using the negative energy of exotic matter. "Quantum effects allow some negative energy," explains Jafferis. "But it was long suspected that what is required for a traversable wormhole is physically impossible."

Now, Jafferis and his colleagues Dr Ping Gao and Dr Aron Wall think they've discovered another source. "What we found is that a direct interaction between the [black holes at the] two ends of a non-traversable wormhole can lead to negative energy," says Jafferis. The resulting anti-gravitational effect then stops the Einstein-Rosen bridge from collapsing, therefore making the wormhole traversable.

When Jafferis and his colleagues say "direct interaction", they mean that the two black holes forming the mouths of the wormhole are affecting each other across real, ordinary space. "Binary black hole systems consuming each other's Hawking radiation is a good example," says Jafferis. "The consuming of the radiation is the direct connection."

### IN A TANGLE

So, the good news is that traversable wormholes really can exist. Better still, according to Jafferis there's no problem sending a human through one of them, at least in principle. But, perhaps unsurprisingly, there are some major problems to overcome. First, the black holes can't just be the standard type formed from the collapsed remnants of huge stars; they have to be maximally entangled. This refers to a strange quantum connection that can exist between two objects, so that anything done to one affects the other instantly – no matter how far apart they are.

Like negative energy, the bizarre phenomenon of quantum entanglement really exists. It was first detected in lab experiments nearly 40 years ago and it's now being investigated by companies like Google for creating ultra-fast quantum computers. Yet while subatomic particles can be entangled relatively easily in the lab, no one has any idea how to do the

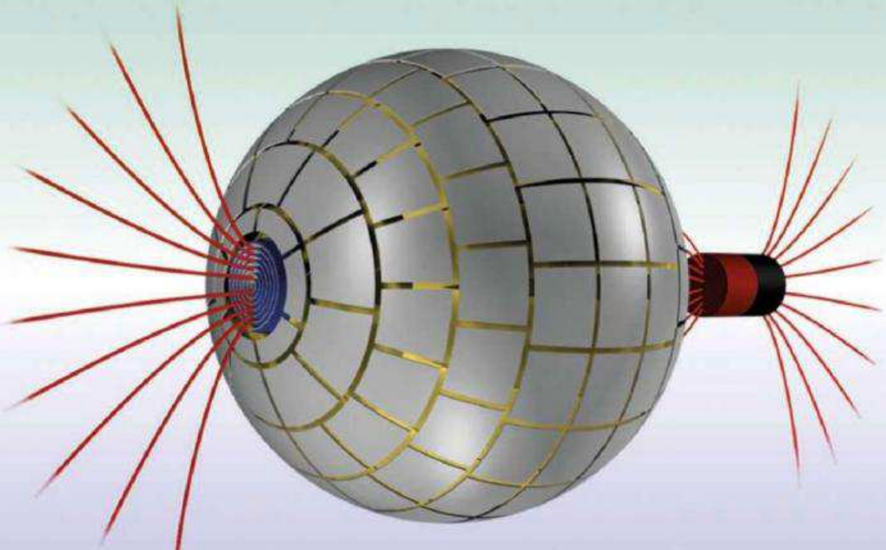


## CREATING A REAL-LIFE WORMHOLE IN THE LAB

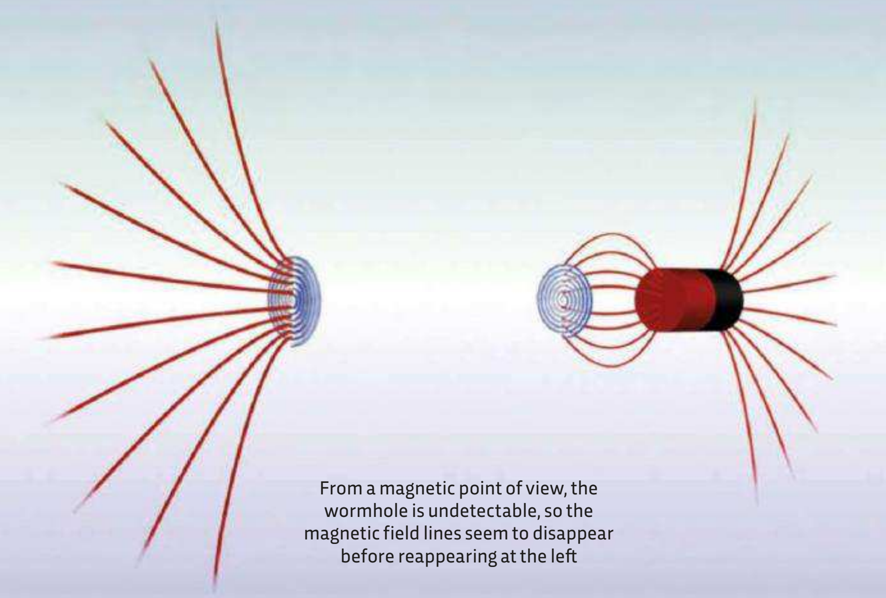
**While theorists wrestle with the possibility of cosmic wormholes, researchers in Spain have succeeded in making one in the lab – by swapping gravity for magnetism. The result is a wormhole that takes magnetic fields in at one place and then allows them to magically reappear somewhere else.**

**Alvaro Sanchez and his colleagues at the Autonomous University of Barcelona pulled off this feat by creating a sphere made from special conducting materials that respond to magnetic fields in different ways. Carefully arranged in layers, these materials have the effect of modifying the way empty space transmits magnetic fields.**

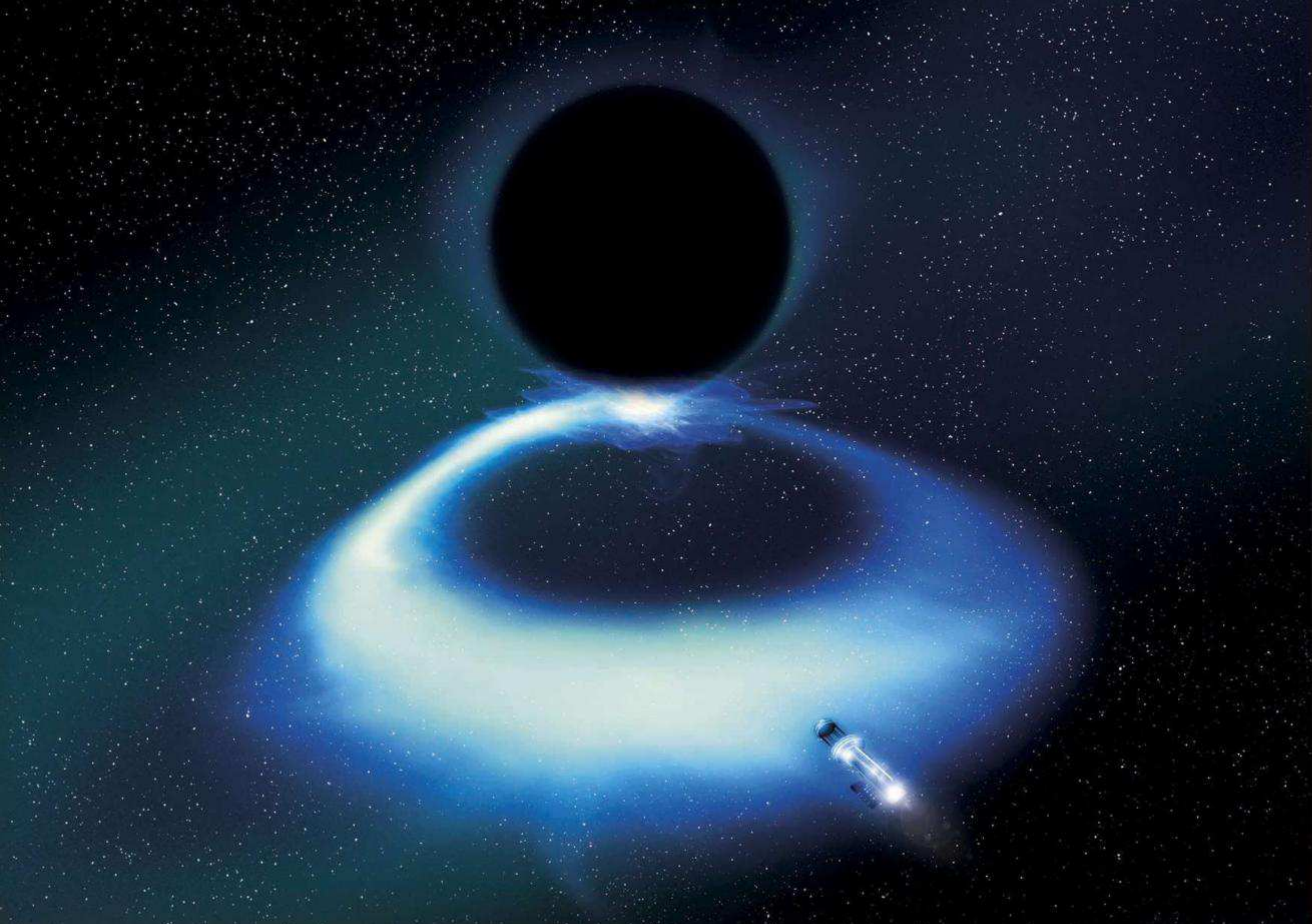
**The result is a device that acts as a wormhole where a magnetic field enters on one side of the sphere, completely disappears once inside, and then appears again on the other. This is no mere party trick, either. The wormhole device allows magnetic fields to travel from place to place without affecting anything on the way. According to the team, it has many applications – such as in MRI scanners in hospital. Instead of having to lie claustrophobically close to the magnetic coils needed to create MRI images, patients could have the magnetic field sent to them from a separate room via the magic of the wormhole.**



Three-dimensional image of the magnetic wormhole. On the right is a small magnet, and you can see how its magnetic field lines exit the other side of the wormhole



From a magnetic point of view, the wormhole is undetectable, so the magnetic field lines seem to disappear before reappearing at the left



**The mere possibility of black holes was disputed for decades, and Einstein himself refused to believe in quantum entanglement**

same with black holes. “We can’t even make unentangled black holes, let alone precisely quantum entangled ones,” explains Jafferis.

Yet direct interaction between two black holes comes with a catch: it forbids any amazing time travel trickery. But could it still allow faster-than-light travel? That’s a tricky question, says Jafferis. Gravity, space and time are all intimately linked, and that messes with the very notion of speed. According to Jafferis, calculations based on the wormhole types studied so far suggest that using them would actually be slower than simply travelling directly through space. He admits, though, that the details have yet to be fully worked out. So, it seems that science fact is still running a little behind science fiction. The laws of nature seem to insist that wormholes can either perform amazing feats but collapse in an instant, or be traversable but useless.

Yet time and again, nature has sprung big surprises on theorists. The mere possibility of black holes was disputed for decades, and Einstein himself refused to believe in quantum entanglement. Could it be that somewhere in the Universe lie natural wormholes performing their miracles?

### SCIENCE OR SCI-FI?

The possibility of observing a real-life wormhole is now the focus of research by theorists using a mix of mathematics and computer models. The challenge is spotting the difference between normal black holes and those that are the portals of wormholes. According to Rajibul Shaikh, a gravity theorist at the Tata Institute of Fundamental Research in Mumbai, India,

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the answer may lie in subtle differences in the way they affect their surroundings – and in particular the behaviour of light. "As predicted by Einstein's General Relativity, photons undergo bending in a gravitational field," he says.

The intense gravity of black holes creates incredibly hot, bright accretion discs around them, formed of matter spiralling down to its doom. The otherwise invisible hosts of these discs then reveal their presence as a pitch-black shadow cast on them. It's the shape of this shadow that could reveal when a black hole is actually something even more bizarre. According to Shaikh, the telltale signs of a wormhole come from the gravitational effect of its throat on the resulting shadow.

"What I found is that the shape of the shadow of a slowly rotating wormhole would be very similar to the almost perfectly disc-like shadow cast by a slowly rotating black hole," he explains. "But a faster spinning wormhole would cast a shadow, which is more distorted than that of a black hole with the same spin."

He stresses that research is still in progress, and the results so far are based on specific types of black holes and wormholes. "There's no guarantee the type of rotating wormholes I considered are the most common."

But Shaikh points out that astronomers already have the means to detect the effects predicted to exist around wormholes. The Event Horizon Telescope (EHT), which we discussed on page 73, has a global network of radio antennas able to make studies of black holes and wormholes. "And it's already started taking data," says Shaikh.

It could just be that, half a century after it made its debut on movie screens, the space-time wormhole is about to become more than just science fiction.

**Robert Matthews** is visiting professor in science at Aston University, Birmingham.

BBC RADIO 4

Listen to an episode of *The Infinite Monkey Cage* which discusses why wormholes could be inaccurately named ***bbc.in/2LIOFBt***

LEFT: In future, could we travel to black holes to capture samples of Hawking radiation to help improve our understanding of wormholes?

BELOW: Scientists can study the shadow that a black hole casts on its hot, bright accretion disc. Certain shapes of shadow may reveal that the black hole is, in fact, a wormhole

# THE SEARCH FOR DARK MATTER

For decades, top astronomers have been on an enormous treasure hunt for the Universe's most mysterious substance. We can't see it, so how do we know it even exists?

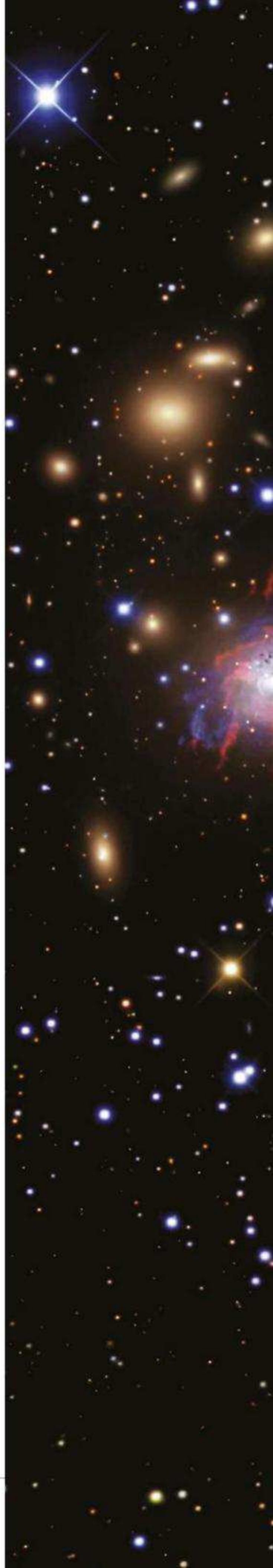
WORDS: **COLIN STUART**

**WHY DO SCIENTISTS THINK THAT DARK MATTER EXISTS?**

The first clues that everything in the Universe was not as it seemed came in the 1930s. Swiss-American astronomer Fritz Zwicky was looking at a group of galaxies and working out how fast the individual galaxies were moving. To his surprise, he found them careering around at speeds far greater than he expected. In fact, they were moving so fast that they should have quickly dispersed, breaking away from the gravity of everything else in the cluster. Except they weren't. Zwicky surmised that there must be more stuff in the cluster that was boosting its overall gravitational pull and keeping the galaxies tied together. The discrepancy wasn't small either. He estimated there was 400 times more matter present than he could see. At a loss to explain what this mysterious material was, he simply called it 'dunkle materie' – the German for dark matter.

Around the same time, Dutch astronomer Jan Oort was forced to invoke something similar. He was looking at the stars orbiting near the edge of the Milky Way. He expected to find that the further he looked from the galactic centre, the slower the stars would be rotating around it. This idea isn't dissimilar to our Solar System: the further a planet is from the Sun, the longer it takes to orbit it. But that's not what Oort found. The outer stars were zipping about faster than they should be. In order to explain why they stayed bound to the Milky Way despite their lofty speeds, he supposed there was some invisible material with gravitational power spread throughout the Galaxy. By 1980, American astronomer Vera Rubin had spotted the same effect in around 100 other galaxies. Whatever this invisible stuff was, it was widespread.

Today, an effect known as gravitational lensing provides even more evidence to suggest there is something strange going on. If we see a large amount of mass, say a cluster of galaxies, move in front of a distant light source, then the foreground object is able to bend the light



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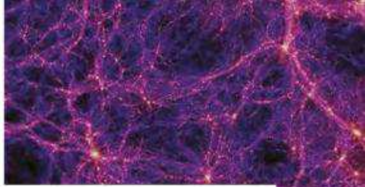
The Perseus Galaxy Cluster (Abell 426) lies about 250 million light years from Earth towards the northern constellation of Perseus. It is comprised of over 500 galaxies including NGC 1275. This view stretches approximately 1.5 million light years wide.



from the background object around it. This light creates a series of arcs that can join together to form what's known as an 'Einstein ring'. The more mass there is, the greater the amount of bending. Yet there is often not enough visible mass in the cluster to account for the amount of bending we observe. Again, there must be extra mass that's hidden from view.

### WHAT DO SCIENTISTS THINK DARK MATTER IS?

Physicists have a cookbook for the Universe known as the Standard Model of particle physics. By using its recipes, they can account for the behaviour of forces and the way particles interact with one another. This model has been validated many times over, including by experiments at CERN's Large Hadron Collider. The book's final missing page was the Higgs boson, discovered in 2012 (see page 6).

And yet there is nothing within those recipes that allows physicists to cook up anything with the observed behaviour of dark matter. It has to be able to interact with normal matter via gravity, and yet in order to remain hidden it cannot interact with light. In an attempt to explain this behaviour, physicists have come up with a new type of particle: Weakly Interacting Massive Particles (WIMPs). They are 'weakly interacting' because they don't interact with light, and 'massive' because they interact via gravity.

When astronomers run computer simulations of a Universe that evolves with dark matter in the form of WIMPs, they get a structure that is a pretty solid match for the distribution

## This light creates a series of arcs that can join together to form an 'Einstein ring'

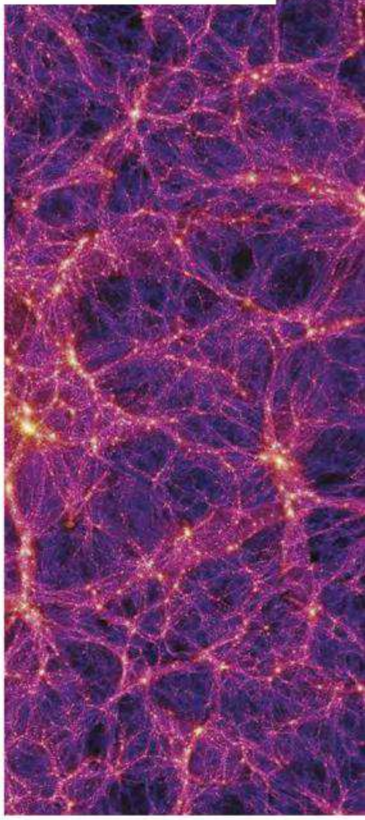
of galaxies that we see today. A theory for physics beyond the Standard Model called supersymmetry also seems to fit with this.

Other explanations have been considered in the past, including MACHOs. Standing for MAssive Compact Halo Objects, the idea is that there are big objects such as black holes ghosting unseen through the Milky Way. When we add up all the mass we can see, we aren't including them, hence why we underestimate the mass of the Galaxy. However, observations and modelling of the early Universe has cast significant doubt over this idea. For now, WIMPs is definitely the frontrunner.

### WHAT ARE SCIENTISTS DOING TO FIND DARK MATTER?

How do you find something that is, by definition, hidden from view? You certainly can't see it. To make things worse, WIMPs are so ghostly that they almost always pass straight through normal matter – including any detector you build to snare one. To put it into perspective, dark matter is so abundant that billions of dark matter particles are streaming unhindered through you every single second. And yet, on average, in any five-minute period only one of these dark matter particles interacts with an atom of normal matter in your body.

This idea that dark matter particles do occasionally deign to interact with normal



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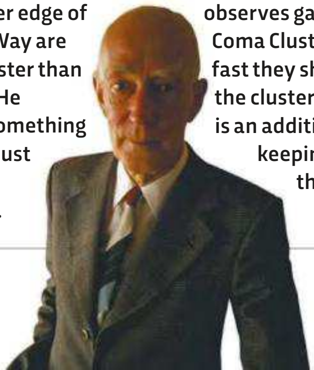
## TIMELINE

*The scientific breakthroughs that have aided our understanding of dark matter*

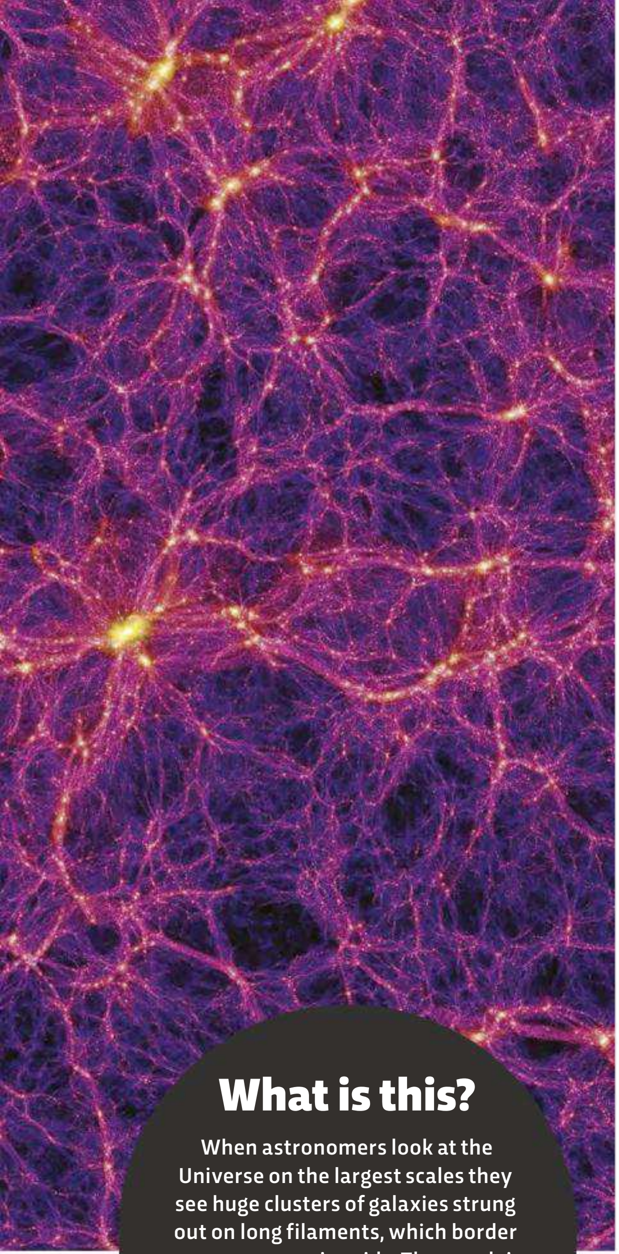
**1932**
Dutch astronomer Jan Oort (1900-1992) discovers that the stars on the outer edge of the Milky Way are orbiting faster than expected. He assumes something invisible must be holding onto them.



**1933**
Swiss-American Fritz Zwicky (1898-1974) observes galaxies in the Coma Cluster moving so fast they should escape the cluster, unless there is an additional material keeping hold of them.

**1937**
US astronomer Sinclair Smith (1899-1938) finds a similar effect to Zwicky's in the Virgo Cluster of galaxies. Smith dies of cancer just one year later at the age of 39.

**1966**
Japanese physicist Hironari Miyazawa (1927-) is the first to put forward a version of supersymmetry, an idea that goes beyond the Standard Model and might explain what dark matter really is.



matter is the basis for the Large Underground Xenon (LUX) experiment deep under the surface of South Dakota in the US. Scientists have commandeered an abandoned gold mine and set up a dark matter detector 1.6km (one mile) down. Consisting of 370kg of liquid xenon shielded by 264,979 litres of water, it is designed to pick up the occasional WIMP interacting with the xenon. Should a WIMP recoil off a xenon atom, the atom is accelerated through the liquid, causing a flash that can be picked up by the surrounding banks of super-sensitive cameras.

Scientists might also be able to detect dark matter when it interacts with itself in a process known as annihilation. When this happens, it is thought a cascade of 'normal' particles is produced and we should be able to pick that up. One such experiment is the Alpha Magnetic Spectrometer (AMS-02) currently strapped to the International Space Station. It is trying to pick up evidence of atomic shrapnel coming from WIMP annihilations near the galactic centre.

The Sun could help too. As the biggest thing in the Solar System it should be acting as a giant cosmic vacuum cleaner, sweeping up dark matter particles as it treks through the Galaxy. Some of the dark matter particles should annihilate inside the Sun, producing a stream of normal particles. Unfortunately, the Sun is so dense that almost all of these daughter particles remain trapped inside. However, one type of particle – neutrinos – would make it out and travel across space to us. Experiments such as IceCube, stationed on Antarctica, are set up to gather these telltale signals.

## What is this?

When astronomers look at the Universe on the largest scales they see huge clusters of galaxies strung out on long filaments, which border enormous cosmic voids. They explain this distribution by suggesting dark matter provides a 'scaffold' by drawing ordinary matter together with its gravitational influence.

## JARGON BUSTER

**DARK MATTER ANNIHILATION**
The process by which two dark matter particles come together, creating a cascade of new particles. We're attempting to detect this with various experiments around the world and in space.

**GALAXY**
A large collection of stars in space, like a city for stars. Ours is called the Milky Way and has around 200 billion stars.

**GRAVITATIONAL LENSING**
A prediction of Einstein's General Theory of Relativity, which says that mass bends light. However, astronomers often see more bending than the amount of visible material present would suggest.

**NEUTRINO**
A small, almost massless particle created by nuclear reactions inside the Sun. Additional neutrinos may be created by dark matter annihilations and detecting them would be a big breakthrough.

**STANDARD MODEL**
The recipe book that particle physicists use to explain a lot of the subatomic world. It contains rules regarding how particles interact with forces and light.

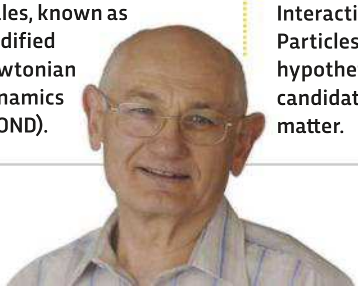
**SUPERSYMMETRY**
An idea that goes beyond the Standard Model and says every 'normal' particle has a supersymmetric partner particle. The lightest of these supersymmetric particles could be responsible for dark matter.

### 1980

US astronomer Vera Rubin (1928-) publishes a landmark paper showing the same effect that Oort observed, but in over 100 other galaxies. Our neighbour, Andromeda, was included.

### 1983

Physicist Mordehai Milgrom (1946-) suggests that the strange rotation of stars in galaxies could be explained if gravity varied on different scales, known as Modified Newtonian Dynamics (MOND).



### 2009

Construction on the LUX experiment begins in South Dakota. The experiment aims to detect Weakly Interacting Massive Particles (WIMPs), a hypothetical particle candidate for dark matter.

**86**

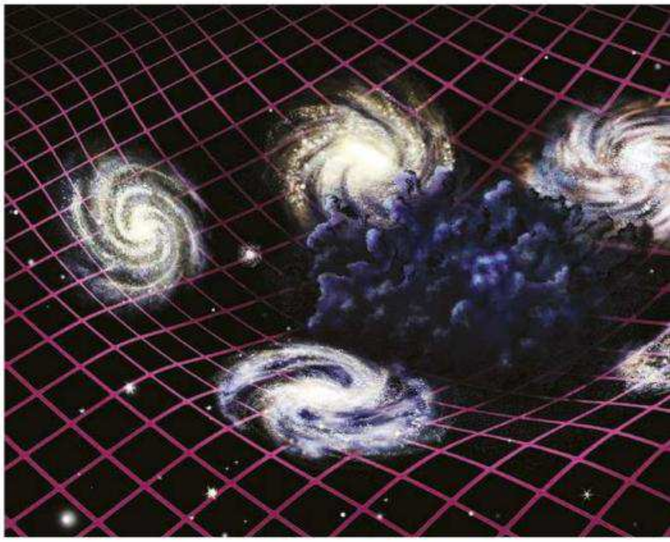
strings carrying detectors were lowered 2,500 metres below the surface of the Antarctic ice as part of the IceCube experiment. This is hunting for evidence of dark matter annihilations.

**264,979**

litres of water are needed to shield the subterranean LUX dark matter detector from being contaminated by radiation from the Earth's surface.

**13**

terraelectronvolts is the record-breaking energy with which the new souped-up Large Hadron Collider is smashing particles together to unlock the secrets of dark matter.



TOP: Chile's Large Synoptic Survey Telescope will help us scour the skies for dark matter

ABOVE: Illustration of five spiral galaxies on a space-time grid, with dark matter at their centre

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Then there is the Large Hadron Collider (LHC). On 5 May 2015 the experiment began smashing protons together after a two-year shutdown designed to boost the machine's power. It is hoped that by colliding particles together with greater energy than ever before, nature might begin to reveal more secrets of its inner workings. Perhaps we will even glimpse evidence of supersymmetry, the theory that goes beyond the Standard Model and is consistent with a WIMP explanation of dark matter. Crucially, however, if the LHC continues to find no evidence for supersymmetry then it may fire the starting gun in the race to find an alternative explanation for why so much of the Universe's mass appears to be 'missing'.

### WHAT'S THE LATEST BREAKTHROUGH?

Signals from stars that formed during the Universe's infancy may provide the first direct evidence of dark matter.

The signals, which date back more than 13 billion years to the period just after the Big Bang when the Universe's first stars were forming, were detected by the EDGES antenna – a radio spectrometer that's located at Australia's Murchison Radio-Astronomy Observatory (MRO). They hold a wealth of information that opens a new window on how early stars, black holes and galaxies formed. But they may also be able to shed some light on the nature of dark matter.

The researchers found the signals embedded in the cosmic microwave background – the electromagnetic radiation left over from the Big Bang that still permeates the Universe today. As stars began to form in the early Universe, light penetrated atoms in the primordial hydrogen gas – surrounding them, internally exciting them and causing them to absorb radiation from the cosmic microwave background at particular frequencies. By locating these dips in frequency, the team was able to determine that the first stars were born just 180 million years after the Big Bang.

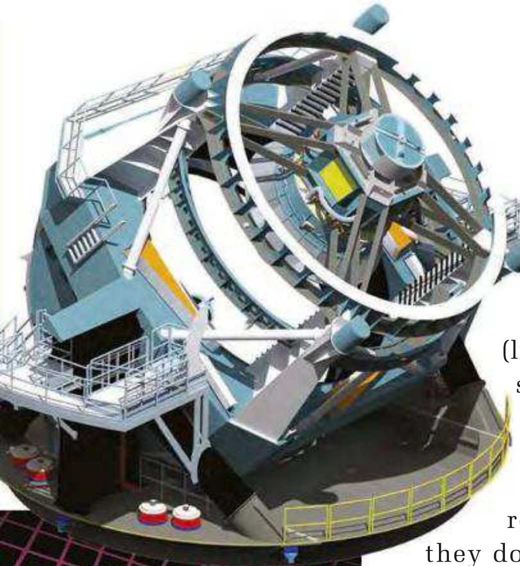
The signals also show that the gas in the early Universe was much colder than expected. According to Tel Aviv University's Prof Rennan Barkana, this could be due to the normal matter interacting with dark matter and losing energy. If he is correct, the finding will be the first direct evidence for the existence of dark matter.

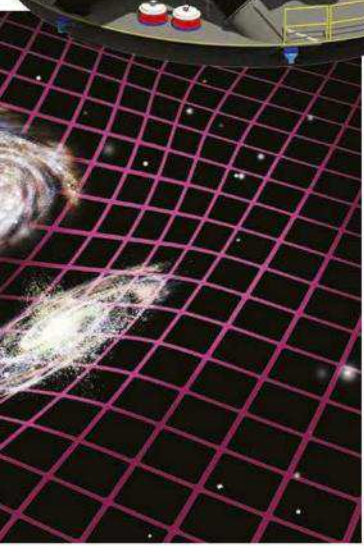
What's more, while many physicists have predicted that dark matter particles would be heavy – so-called Weakly Interacting Massive Particles, or WIMPs – this new discovery indicates that it's more likely to consist of low-mass particles no heavier than several protons. The team is now waiting for researchers at other radio telescopes around the world to confirm their results.

### COULD DARK MATTER BE SOMETHING ELSE?

So far we've been assuming that dark matter is tangible, something that truly exists. But what if it doesn't? What if it's a phantom – a symptom of the fact that we don't understand gravity properly? That's exactly what proponents of a theory called Modified Newtonian Dynamics (MOND) advocate.

Remember, one of the original reasons dark matter was introduced was to account for the fact that stars in the Milky Way don't slow





down the further they are from the galactic centre, unlike the planets of our Solar System. But what if there is one rule for gravity on small scales (like a solar system) and another for large scales (like a galaxy)? While Newton's laws of gravity allow us to send people to the Moon or spacecraft to the planets, stretching those rules to regions to which they don't apply might explain why we're puzzled by the strange motions of stars.

**What if there is one rule for small scales (like a solar system) and another for large scales (like a galaxy)?**

The idea was first put forward by physicist Mordehai Milgrom in 1983. He suggested that the strength of gravity could become stronger where acceleration levels are small (just like at the edge of a spiral galaxy). These ideas can help to explain some details about how galaxies work in ways that the dark matter theory cannot. However, there is currently no reason to suspect that gravity behaves differently on different scales and MOND struggles to explain why galaxies cluster together in the way they are observed to do. A final criticism has been that Newton's picture of gravity is no longer the best gravitational theory we have – that accolade belongs to Einstein's General Relativity. Work continues to try and make the MOND theories 'relativistic'.

BBC RADIO 4

Listen to an episode of *In Our Time* about dark matter *bbc.in/1C81pcb*

### HAS DARK MATTER GOT ANYTHING TO DO WITH DARK ENERGY?

No. Dark energy is the mysterious entity thought to be accelerating the overall expansion of the Universe – a sort of anti-gravity. In contrast, dark matter can be thought of as gravitational glue that helps bind galaxies and clusters of galaxies together. The fact they both share the same adjective indicates our collective ignorance about the true nature of both – we're literally in the dark as to what they are.

### IS THERE A LOT OF DARK MATTER?

Dark matter completely dominates the ordinary matter of which people, planets and stars are made. Our Milky Way is thought to be about 90 per cent dark matter and only 10 per cent 'normal' matter (also called baryonic matter). Of all of the matter in the Universe, 85 per cent is dark matter and only 15 per cent is baryonic.

However, there is one thing to be careful of and that's the distinction between how much of the Universe is made of dark matter and how much of the Universe's matter is dark. According to Einstein's famous equation $E=mc^2$, mass and energy are two sides of the same coin. So cosmologists often talk about the mass-energy of the Universe – all the mass and all the energy put together. In these terms, the Universe is 68 per cent dark energy, 27 per cent dark matter and just 5 per cent atoms. If we discount the energy part, the numbers revert to above – 85 per cent dark matter, 15 per cent baryonic matter.

### HOW WILL THE HUNT FOR DARK MATTER AFFECT ME?

Many technologies often filter down to use in everyday life. Take CERN, for example. The first webpage was info.cern.ch. This technology was devised to communicate between the facility's computers. One likely spin-off from the dark matter hunt is better digital cameras. The Large Synoptic Survey Telescope is currently under construction. By 2022 it should begin to scour the skies. Equipped with the world's largest camera it will be able to map out the structure of the Universe in order to test out theories about dark matter. By building such an enormous camera, those new technologies will eventually end up in the commercial photography and medical imaging markets.

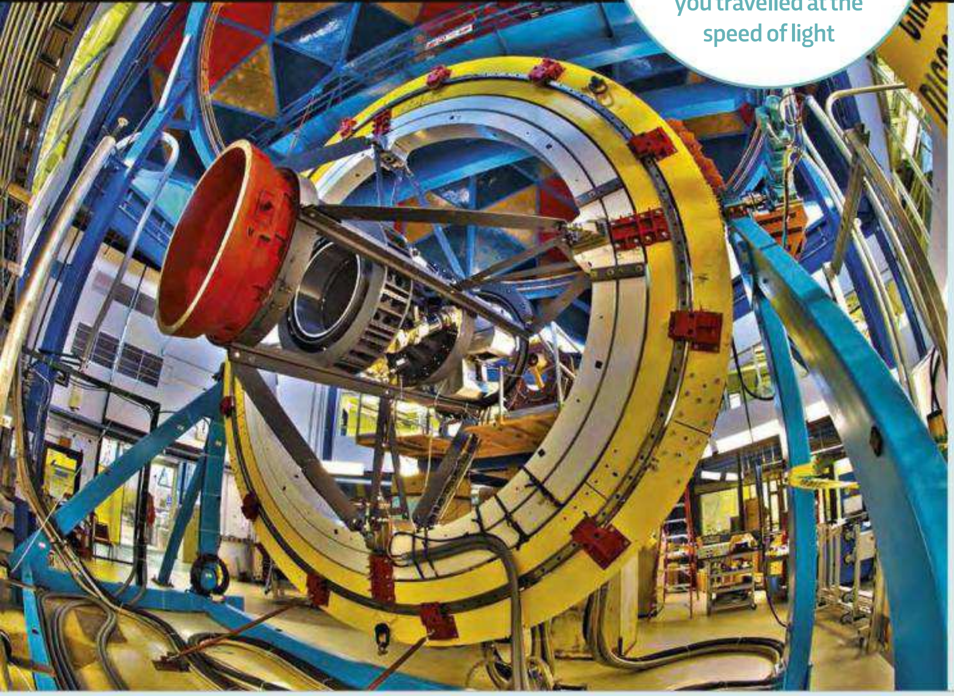
**Colin Stuart** is an astronomy writer and author of *The Big Questions In Science*.

# WHY IS SPACE DARK?

Starlight gets fainter with distance. A simple calculation shows the fading is cancelled out by the ever-increasing numbers of stars with distance, and should therefore leave space ablaze with light. But the Universe is expanding after exploding from the Big Bang around 13.8 billion years ago. As such, stars haven't existed long enough to fill the Universe with their light, which is also stretched and weakened by the cosmic expansion. The result is a Universe as black as pitch.

**7.5**

The number of times you could go around the Earth in one second if you travelled at the speed of light



## WHAT IS DARK ENERGY?

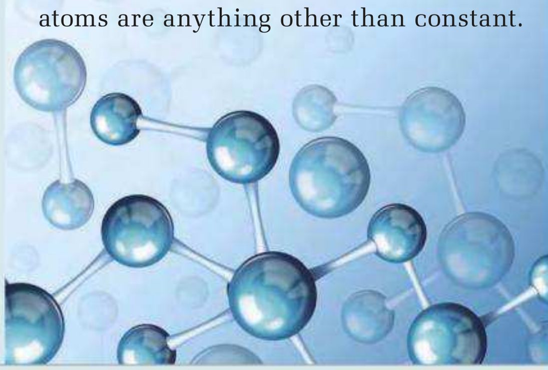
The Universe's expansion is accelerating, as if the whole cosmos is being propelled by some invisible source – dark energy. Various explanations have been put forward. According to the laws of the subatomic world, there is always some uncertainty about the amount of energy filling empty space. This vacuum fluctuation energy has been detected in the lab and shown to have the 'anti-gravitational' effects of dark matter. But, so far, scientists have struggled to produce a detailed theory of its cosmic effects. This has led to suggestions that dark energy may simply be a force-field left over from the Big Bang. Sometimes called quintessence, it's capable of getting stronger over time, but again details remain elusive.

# Q&A

All those mind-bending questions that you've never got round to finding out the answers to...

## Are atoms expanding as the Universe expands?

The expansion of the Universe only significantly affects space and time on scales bigger even than entire clusters of galaxies. Below this, the size of objects is dictated by far stronger influences, notably the force of electromagnetism in the case of atoms. Extremely sensitive measurements have found no evidence that the fundamental properties of atoms are anything other than constant.



## Do all substances have three states of matter?

Far from it: many substances can be found in more than three states of matter, while others have fewer than three. All the chemical elements can be induced to form solids, liquids or gases. But if you superheat a gas, then the electrons get stripped away from the nuclei to form plasma. Stars are made from plasma, so it is the most common state of matter in the Universe.

## IS ANYTHING TRULY RANDOM?

That's a question with practical importance, as randomness is surprisingly useful – such as for simulating the effects of chance on complex systems like stock markets, and for selecting representative samples of patients when testing new drugs.

Researchers typically use random numbers supplied by a computer, but these are generated by mathematical formulas – and so by definition cannot be truly random.

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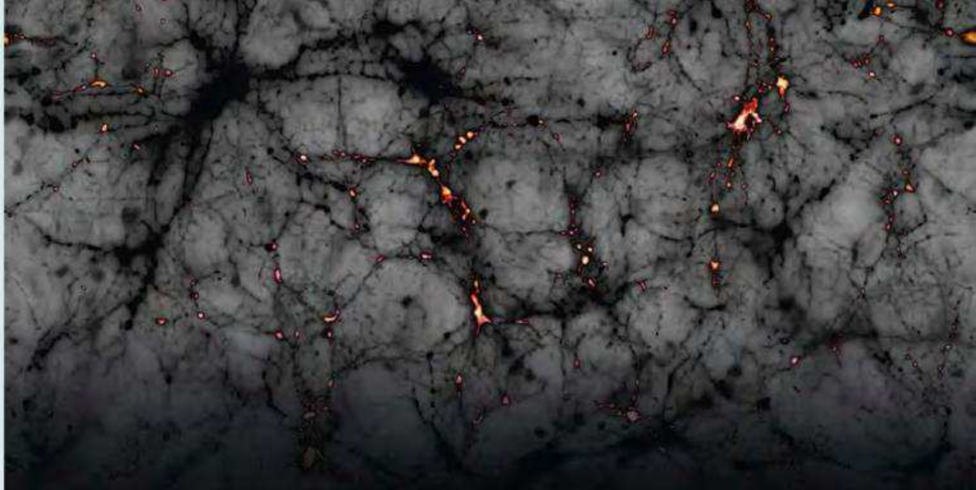
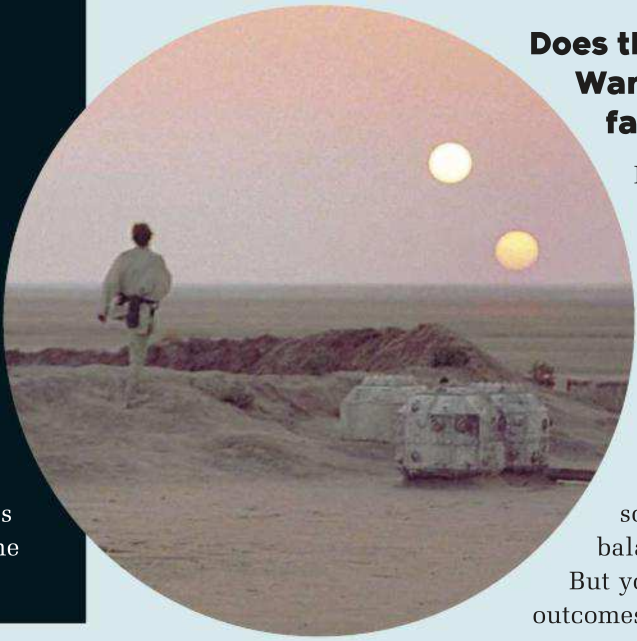


# WHAT IS EXOTIC MATTER?

Exotic matter is the generic name that physicists give to matter with weird properties. Exactly how weird depends on the area of physics. For example, those working in cryogenics – the study of ultra-cold temperatures – work with so-called superfluids, isotopes of helium whose quantum properties allow them to defy gravity, escaping from containers by creeping up and over the walls.

### What would faster-than-light (hyperspace) travel look like?

If we regard hyperspace travel as the ability to travel at almost the speed of light, we can dismiss the idea of stars elongating as shown in films. In fact, as your speed increased, you would see the stars fade and eventually disappear as their light is redshifted into the X-ray part of the spectrum, which is invisible to the human eye. The starlight would be slowly replaced by a diffuse glow, concentrated towards your direction of travel, caused by the cosmic microwave background (the leftover radiation from the Big Bang which fills the entire sky) being redshifted into the visible part of the spectrum.

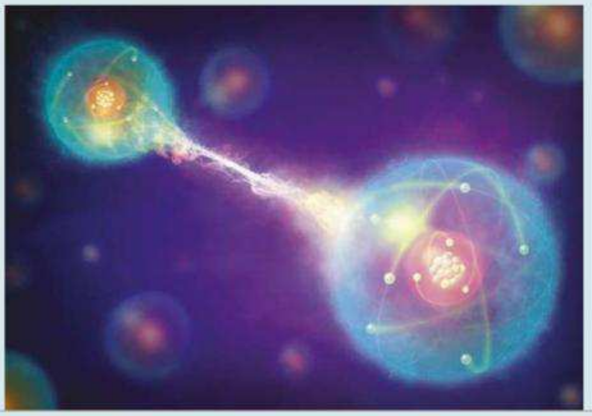


### Does the world of Star Wars exist in a galaxy far, far away?

If quantum physics allows parallel universes, and there are an infinite number, then it's possible that one of them contains the Star Wars galaxy. But it's not inevitable. Imagine the roll of a die across infinite parallel universes. Every possible result will occur somewhere, including the die balancing on one of its edges. But you'll never roll a seven. Some outcomes are just impossible.

## How does entanglement work?

Through a trick of quantum mechanics, you can link two particles in a special way, separate them, and then observe the effects of one upon the other over large distances. This 'quantum entanglement' is placing two objects in the same entangled quantum state. If you measure one particle, the other particle's state will be determined immediately regardless of how far it is away. Einstein didn't like this idea, but modern experiments have shown that entanglement is real – particles can be connected over very large distances.



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# IS SCHRÖDINGER'S CAT DEAD OR ALIVE?

**Over 80 years ago, Austrian physicist Erwin Schrödinger in 1935 came up with a hypothetical experiment in order to understand the weirdness of quantum physics. He imagined a cat sealed in a box containing a radioactive particle and a vial of poison gas. If the particle decayed, the vial would break and the cat would die, but if it didn't, the cat would live. Schrödinger was trying to highlight how if a particle were simultaneously decaying and not decaying, provided no one looked, the cat would be both dead and alive – until someone took a peek. This does actually work at the quantum level – for example, a computer bit can be in a state of '0' or '1', and a so-called qubit (quantum bit) can be in both states at the same time – known as a 'cat state'. This allows the quantum computer to multi-task.**

## COULD WE TIME TRAVEL?

In the grandfather paradox, a time traveller goes back in time and either accidentally or deliberately kills his own grandfather, before the time traveller's father has been conceived. So the time traveller is never born, so he never goes back in time, so his grandad never dies, so the time traveller is born. And so on.

A variation on this theme is used as a key plot device in *Back To The Future*. If Marty McFly accidentally prevents his own parents falling in love and marrying, he will not exist. But as the science fiction writer Robert Heinlein put it, "a paradox can be paradoctored". Marty does change the past, but in a positive way. He comes home to a different, better future than the one he left. But what happened to the 'original' future?

The twin paradox is more sound scientifically. As discussed on page 36, Special Relativity tells us that moving clocks run slow. If one member of a pair of twins goes on a journey at a sizeable fraction of the speed of light, he or she will age more slowly than the twin who stayed at home. When the travelling twin returns, he or she will be younger than the twin who stayed behind. From the point of view of the travelling twin, time has passed more rapidly on Earth. This type of time travel was explored in *Planet Of The Apes*.

**1000**
The depth below the Earth's surface where a lab in North Yorkshire studies dark matter

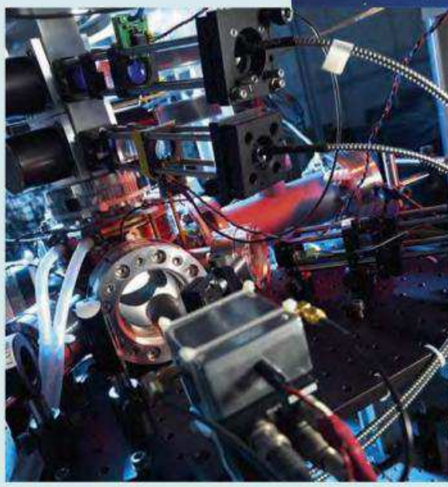
# Where is the centre of the Universe?

As the Universe may not have a physical edge, there is no sense in the idea of an absolute centre. Imagining the centre as the point at which it began is also meaningless. The Big Bang happened everywhere at once and the Universe has been expanding ever since. Every point can be regarded as being at the centre of this expansion. So, the centre of the Universe is nowhere, and everywhere!

**4 million**

The number of suns equivalent to the mass of the black hole at the centre of the Milky Way

BELOW: An atomic clock at the UK's National Physical Laboratory in Teddington



## How do we know what the speed of light is?

Today, highly stable lasers, and the measurement of time intervals using atomic clocks, enable the accurate value of 299,792,458m/s (with just 1m/s uncertainty). The second can be defined precisely using atomic clocks, and the uncertainty in the speed of light is dominated by the accuracy in defining a metre. It has been agreed to 'fix' the speed of light at the above value, and to define the metre so that there are exactly 299,792,458 of them in the distance that light travels in a vacuum in one second. So, instead of measuring the speed of light relative to the space-time of the Universe, we determine the latter from the speed of light.

## Is gravity getting weaker?

During the 1970s, studies of the Moon suggested it was moving away from the Earth. Most of the increase in distance could be explained using standard theories of how the gravity fields of the Moon and Earth interact. But some of the increase pointed to a weakening of the force of gravity itself. However, the original claim is now thought to be the result of faulty analysis of the Moon's orbital motion.

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# WHAT IS A SINGULARITY?

It's a point when matter is infinitely dense and piled on top of itself, such as at the birth of the Universe or at the centre of a black hole. When this happens, the laws of physics completely break down.

In the 1960s and early 70s, recently deceased physicist Stephen Hawking worked with mathematician Roger Penrose on how singularities could form. It was one of the most fruitful collaborations in 20th-Century physics. Their most important discovery was that under a wide range of general and highly plausible conditions, the Big Bang singularity was unavoidable.

Science is full of incredible concepts like the quantum world, multiverses, space-time, dark matter and wormholes. In this special issue, experts help you get to grips with the biggest and most mind-bending ideas out there.

FROM THE MAKERS OF ***BBC FOCUS*** MAGAZINE